Report on the building energy simulation models of an office building, a retirement home, a school, and a block of flats

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Contents

Chapter 1

Introduction

This document describes the Modelica building energy simulation models of four different types of buildings: an office, a retirement home, a school, and a residential building. Each chapter is structured as follows: Section 1 elaborates on the model (building envelope, HVAC, boundary conditions, rule based control, model validation), and Section 2 presents some simulation results.

The authors gratefully acknowledge the financial support by IWT and WTCB in the frame of the IWT-VIS Traject SMART GEOTHERM focusing on integration of thermal energy storage and thermal inertia in geothermal concepts for smart heating and cooling of (medium) large buildings. The authors further would like to thank Boydens Engineering and Aco bouwteam for sharing their building plans and parameters.

Chapter 2

Office building: Hollandsch Huys

- **Type of building**: Office building
- **Simulation Software**: Modelica - Dymola
- **Modelica libraries**: IDEAS v.1.0.0, Buildings v.3.0.0, Smartgeotherm v.1.0.0.

The case study building, called *Hollandsch Huys* is located in Hasselt, Belgium. Its construction was finished in 2007. Designed to be a low-energy, innovative office building, the building is a pure *GEOTABS* building. It makes use of thermally activated building systems (TABS), in which the thermal mass of the concrete floors is *activated* by a water piping circuit for both heating and cooling. The ventilation system is composed of a recovery wheel with by-pass, a heating and a cooling coil and the injection and extraction fans are on-off controlled. The heat and cold are produced by a ground-coupled heat pump.

1 Model description

The building consists of five floors: an underground parking, three floors and a roof apartment (the latter not modelled). The following sections describe the building envelope (section 1.1), the heating, ventilation and air handling unit (HVAC) (section 1.2), the occupancy and internal gains assumed for the model (section 1.3), the rule based control (RBC) (section 1.4), and the model validation (section 1.5).

1.1 Building envelope

The general parameters of the building envelope are summarized in table 2.1. In order to simplify the model, the building is divided in 12 thermal zones as depicted by fig. 2.1. The corresponding zone indices in the model are marked on figs. 2.15 and 2.16 (see Appendix A). All transparent parts of the façade are equipped with triple glazing. The window surface lies 40 cm deeper than the façade. Each of them is equipped with an external slat shading device whose angle

Table 2.1: General building parameters.

Floor area	[m^2]	3760	U-value	[W/m^2/K]	0.216
Conditioned volume	[m^3]	10526	Loss area	[m^2]	4438
Window-to-wall ratio	[-]	34%	ACH (n50)	[1/h]	0.9

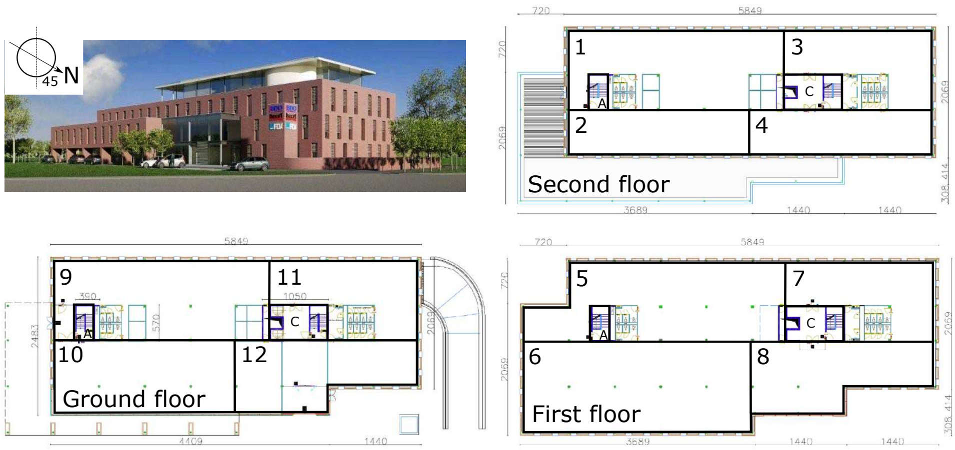


Figure 2.1: Zone layout.

is adjusted automatically to the solar radiation intensity: the shading device is controlled by a hysteresis controller which closes the shading when the horizontal solar radiation exceeds 150 W/m^2 and re-opens it when the solar radiation is lower than 80 W/m^2.

1.2 HVAC System

The building is a *hybrid GEOTABS* building. Its emission system is composed of TABS and floor heating and the production system is a ground coupled heat pump. An additional gas-boiler is installed in the real building to back up the heating of the ventilation air but it is not included in the model as it is not needed when proper control is used. The ventilation system is composed of a recovery wheel with by-pass, a heating and a cooling coil and the injection and extraction fans are on-off controlled.

1.2.1 Heat / cold production and emission

Figure 2.2 shows the hydraulic scheme of the building. The emission system is composed of floor heating at the ground floor, of TABS with a floor and a ceiling circuit between the different floors of the building, and of TABS with a ceiling circuit in the roof. The nominal mass flow rates are listed in table 2.2. The production system is composed of a borefield, two buffer tanks of 2 m^3 each, three heat exchangers, some circulation pumps and a heat pump of 181 kWth. Notice that the heat pump of the real building is a Daikin EWWP145 KAW1M which consists of three modules that can be separately controlled. In the model, this heat pump is simplified as a perfectly modulating heat pump with characteristics given by fig. 2.3 (scaled data from the Viessmann heat pump VitoCal300GBWS301.A45). The borefield characteristics are summarized in table 2.3 and fig. 2.4 shows its layout. The borefield of the real building contains 34% of ethylene. In the model, the fluid is simplified to 100% water as the temperature never drops below the freezing point. The nominal mass flow rates of the different pumps are given in table 2.4. Notice that in the model, pump P_9 is actually a set of 29 pumps in parallel which control each individual TABS and floor heating circuit. In reality, the mass flow in each circuit is controlled by a valve and two pumps ensure the pressure head.

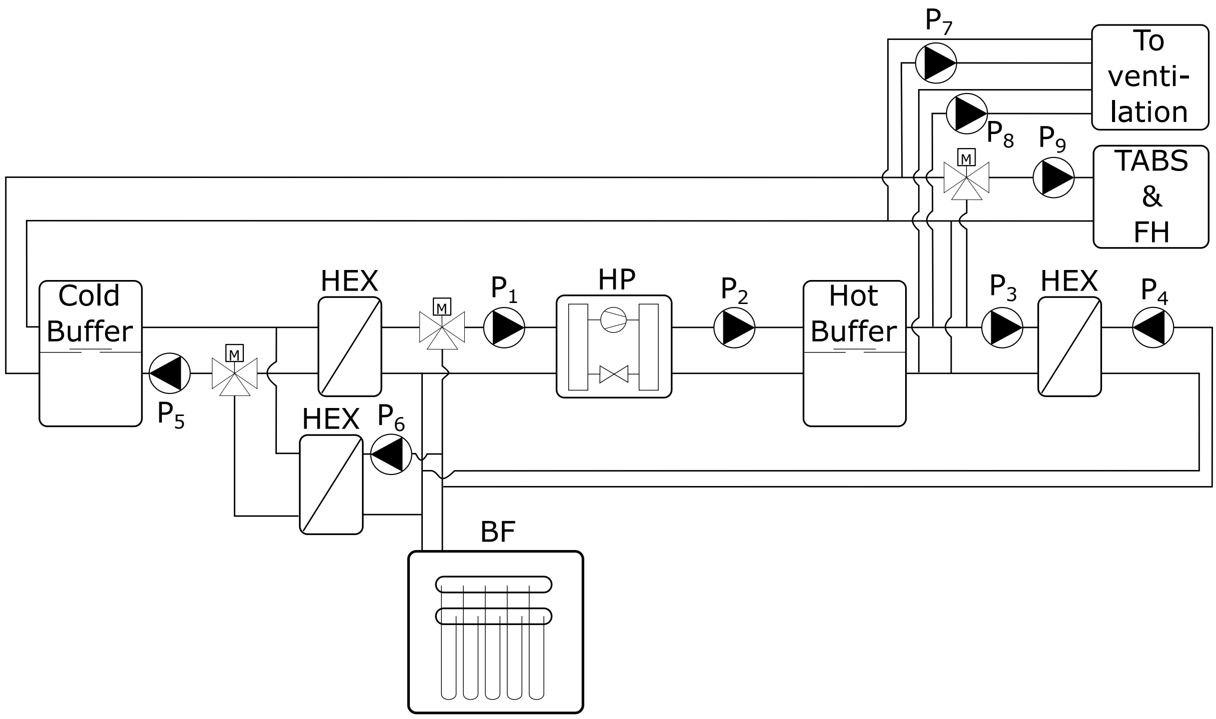


Figure 2.2: Hydraulic scheme. The components are: a borefield (BF), heat exchangers (HEX), buffers, a heat pump (HP), TABS and floor heating (FH) and 9 circulation pumps P_i.

Table 2.2: Nominal mass flow rates for TABS and floor heating.

Emission	Nominal mass flow rate			
TABS-ceiling	7	[l/h/m^2]	0.0019	[kg/s/m^2]
TABS-floor	6	[l/h/m^2]	0.0017	[kg/s/m^2]
Floor heating	4	[l/h/m^2]	0.0011	[kg/s/m^2]
Entire building	47600	[l/h]	13.22	[kg/s]

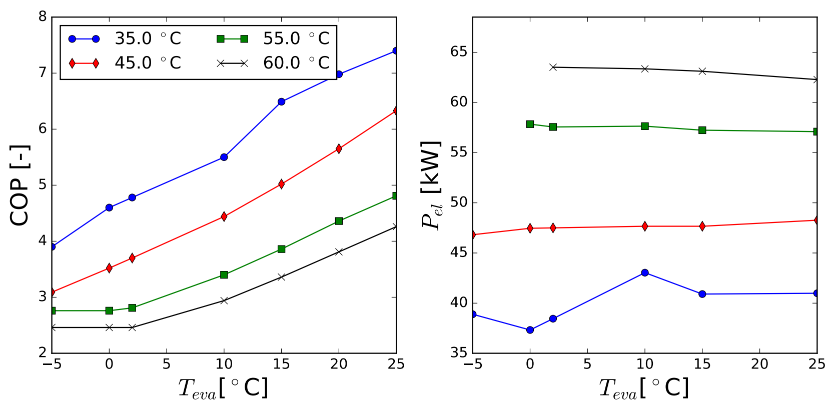


Figure 2.3: Heat pump characteristics as a function of the evaporator inlet and different condensor outlet temperatures, scaled from the characteristics of the heat pump VitoCal300GBWS301.A45 of Viessmann [12].

Table 2.3: Borefield parameters.

Layout			Borehole			Ground			Grout		
# bh	14+8	[-]	D_{bh}	160	[mm]	T_0	11.3	[°C]			
Type	1U	[-]	D_{pipe}	32	[mm]	λ	2.2	[W/(m.K)]	λ	0.6	[W/(m.K)]
H	75	[m]	e_{pipe}	2.9	[mm]	ρ	1000	[kg/m^3]	ρ	1000	[kg/m^3]
R_b	0.266	[(m.K)/W]	λ_{pipe}	0.38	[W/(m.K)]	c_p	2470	[J/(kg.K)]	c_p	1650	[J/(kg.K)]

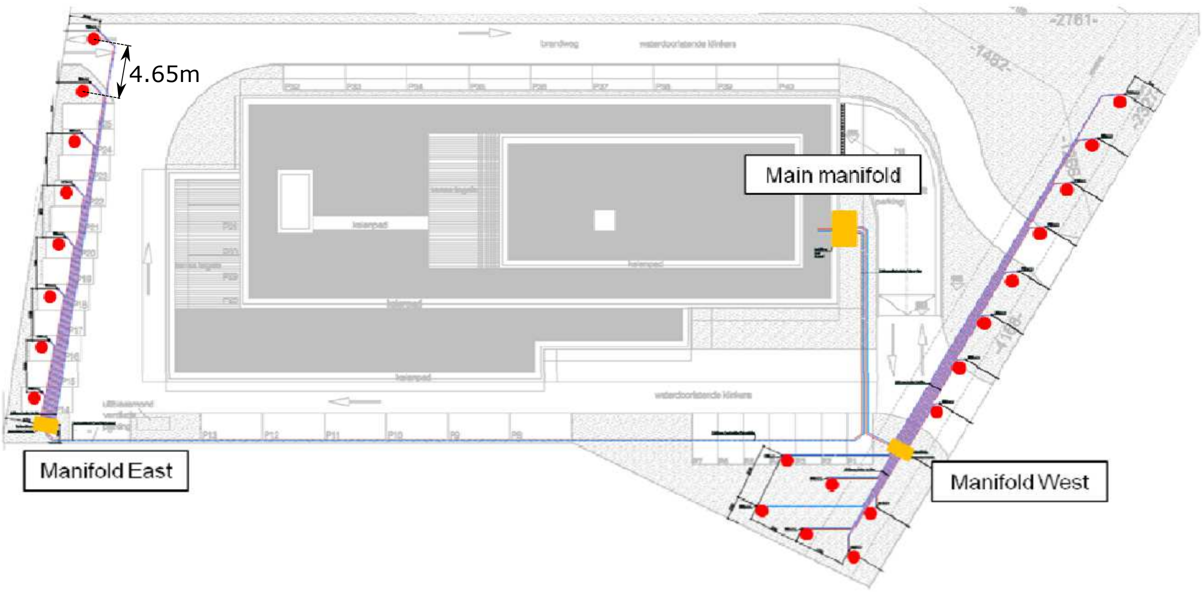


Figure 2.4: Borefield layout.

Table 2.4: Nominal mass flow rates of the different pumps indicated in fig. 2.2.

		P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
$\dot{m}_{\text{nom}}$	[l/h]	48984	48984	48984	48984	48984	48984	1392	1392	47592
	[kg/s]	13.61	13.61	13.61	13.61	13.61	13.61	0.39	0.39	13.22

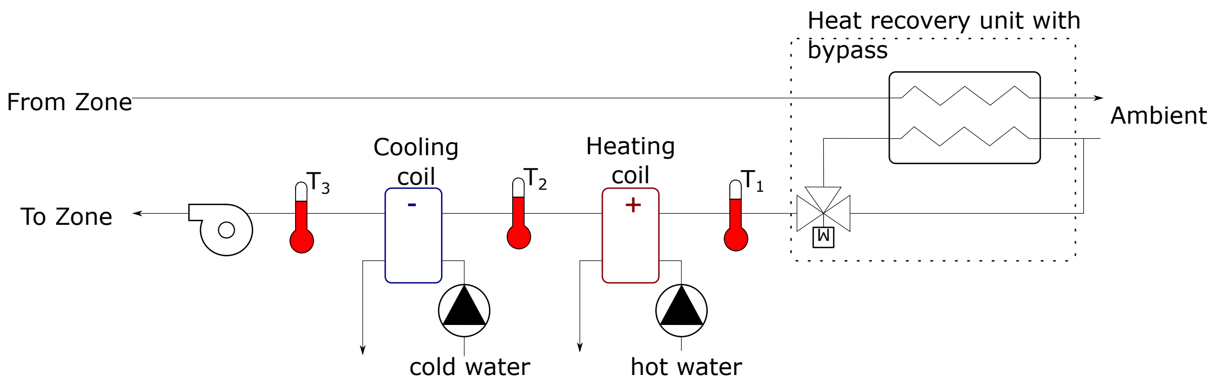


Figure 2.5: Schematic drawing of the ventilation system.

Table 2.5: Nominal ventilation flow rates.

Type of room	Nominal mass flow rate			
Office area	1.80	[m^3/h/m^2]	6.01E-4	[kg/s/m^2]
Technical room	0	[m^3/h/m^2]	0	[kg/s/m^2]
Entire building	6787.50	[m^3/h]	2.26	[kg/s]

1.2.2 Ventilation

The ventilation system is composed of a heat recovery with by-pass, a heating and coiling coil, a supply and an extraction fan. In the real building, the heating coil can be connected to a gas boiler in the case the heat pump can not deliver the necessary heat power. For simplicity, the model only has a supply fan, the coil is split into a heating and a cooling unit and the gas boiler is omitted. A schematic representation of the ventilation model is given by fig. 2.5. The ventilation return flow is only 95% of the supply flow due to air losses. The ventilation works at nominal condition when occupancy is non-zero and it is turned off otherwise (see nominal conditions in table 2.5 and occupancy in fig. 2.6).

1.3 Occupancy and internal gains

The internal gains are computed by the stochastic behavioural model of Parys et al. [8]. Their nominal values are listed in table 2.6. In the model, the nominal values are multiplied by the stochastic coefficients of fig. 2.6.

Table 2.6: Nominal internal heat gains. The actual heat gains are obtained by multiplying the nominal values with the coefficients of fig. 2.6.

		People *			Light		Appliances	
Type of room		Conv	Rad	Lat	Conv	Rad	Conv	Rad
Office area	[W/m^2]	1.63	1.63	2.75	3.50	3.50	6.23	8.60
Technical room	[W/m^2]	0	0	0	0	0	0	0

* (assuming 20 m^2 / person as the building is only partially occupied)

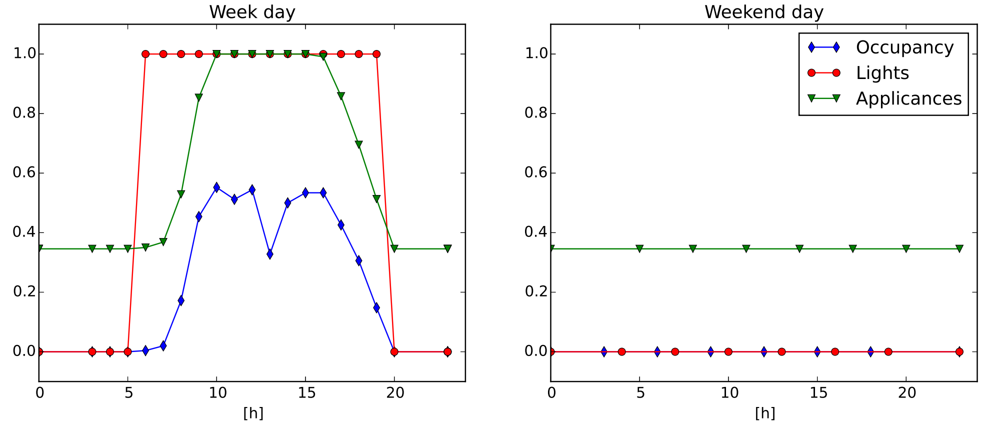
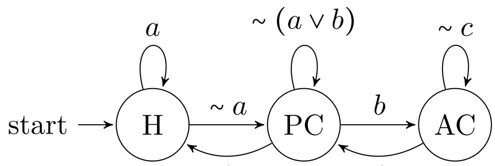


Figure 2.6: Time-dependent coefficients for internal gains. Profiles taken from Parys et al. [8].



$$a = T_{e3d} < 12°C$$

$$b = (T_e > 30°C) \wedge \left(T_{\text{cold,storage,top}} > T_{\text{cold,storage,set}} + 10°C\right)$$

$$c = \left(T_{\text{cold,storage,top}} < T_{\text{cold,storage,set}}\right) \vee (T_{e3d} < 30°C)$$

Figure 2.7: Mode selection between the heating (H), the passive cooling (PC) and the active cooling (AC) mode. T_e and T_{e3d} are the ambient temperature and its 3-day average, respectively. $T_{\text{cold,storage,top}}$ is the temperature in the highest layer of the cold storage tank and $T_{\text{cold,storage,set}}$ its set-point. $\vee$ is the logical conjunction (and), $\wedge$ the logical disjunction (or), and $\sim$ the negation (not).

1.4 Rule based control

The building control is based on three different modes: the heating (H), the passive cooling (PC) and the active cooling (AC) mode. The controller can switch from mode to mode according to the finite state machine as described in fig. 2.7. The transitions are only evaluated at the start of each hour in order to avoid a too fast switch between the modes. Depending on the mode, the production system can either heat, cool using the passive cooling or cool using the active cooling function of the heat pump. The working principle of the production system is shown for each mode in fig. 2.8.

In H mode, the temperature of the hot storage tank is controlled using a PI-controller which modulates the heat pump. Its measured input is the temperature of the highest layer of the hot

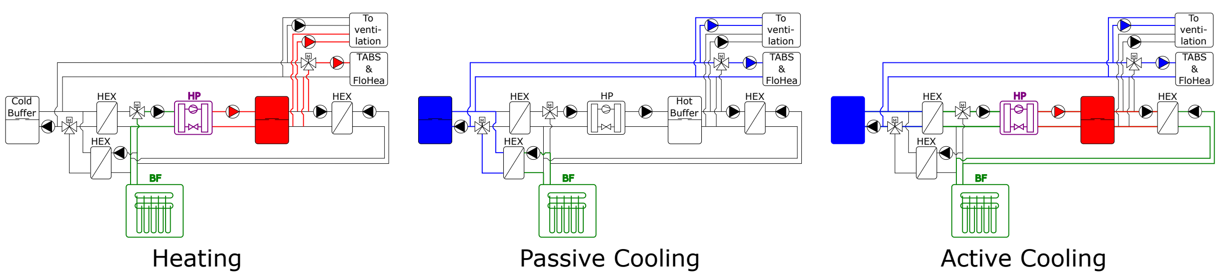
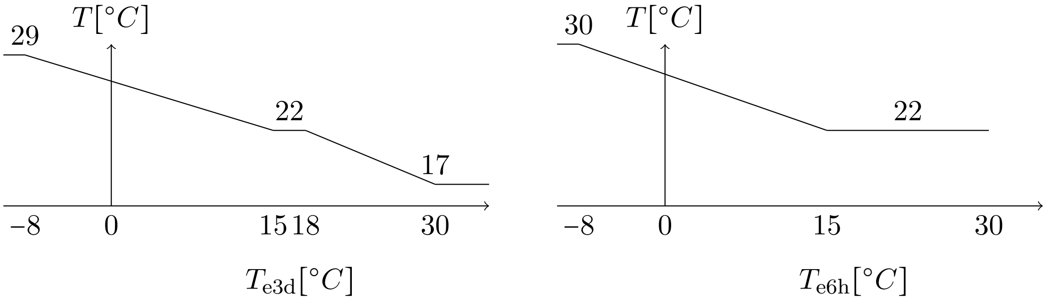


Figure 2.8: Working principle of the production system as a function of the mode.



(a) Heating curve for TABS (b) Heating curve for floor heating.

Figure 2.9: Heating curves for the supply water to the TABS (a) and to the floor heating system (b) as a funcion of the previous three days (3d) and previous 6 hours (6h) average ambient temperature (T_e).

Table 2.7: Re-circulation times for TABS and floor heating as a function of the difference between the supply temperature (T_{sup}) and the return temperature (T_{ret}).

T_{sup}-T_{ret}	[K]	3	5	7	9	9+
Extra re-circulation time	[s]	0	600	1200	2000	3000

buffer tank and its set-point is the maximum of the heating curve for the TABS and the one for the floor heating (see fig. 2.9). The circulation pumps P_1 and P_2 are turned on at nominal condition for non-zero modulation of the heat pump. During the PC mode and the AC mode, the temperature of the cold storage is controlled using a PI-controller which modulates pump P_5. The temperature of the lowest layer of the cold buffer tank is used and the set-point is set by the TABS cooling curve (see fig. 2.9). In the case of the PC-mode, P_6 is turned on for non-zero modulation of P_5. In the case of AC-mode, the heat pump is controlled with the same signal as P_5, P_1 and P_3 are turned on for non-zero modulation and P_4 is only turned on if the temperature of the hot buffer tank reaches its maximum allowed temperature.

The TABS and floor heating circuits are controlled as follows: each hour, the water is circulated in each circuit for 10 minutes. Depending on the difference between its supply temperature and its return temperature, the re-circulation is continued for a given amount of time (see table 2.7). It should be noted that the starting time of the different circuits is shifted by 10 minutes relative to each other in order to smooth the thermal demand loads.

Finally, the ventilation is *on* from 6:00 AM to 8:00 PM. Its supply set-point temperature is set equal to the lower temperature of the comfort range. The supply air is firstly conditioned by the recuperator and the by-pass of the ventilation system. If necessary, the air is further conditioned by the heating or the cooling coil controlled by a PI-controller. The water to the coils is coming from the hot and cold buffer tank. The ventilation can therefore not cool during the H-mode or heat during the PC-mode.

1.5 Model validation

This section is based on Picard et al. [9].

The following paragraphs describe the building monitoring data, the weather data, the tuning of the model and the model validation.

Measurement data. The Modelica model of the Hollandsch Huys building has been validated using 5 sets of measurement data. The first data set was obtained from an experiment conducted in the building during the Christmas holidays of 2012. The building was not or only partially occupied during 11 consecutive days and this opportunity was used to excite the HVAC system with several step inputs: two sequences of whole building cooling down (all HVAC off) and heating up (resp. TABS on and TABS+AHU on), and sequences of active cooling down (TABS cooling on) and heating up (TABS on or TABS+AHU on) of specific zones. These last step inputs are generated to evaluate the intra-zone effect of thermal conditioning. During these experiments, extra zone temperature sensors were installed in addition to the Building Management System (BMS) zone temperature sensors, allowing a more accurate validation for each of the 12 zones.

The other four data sets each contain approximately one month of measurement data during the year 2014: Jan 14-Feb 10; May 9-June 2; June 13-July 7; Aug 23-Sept 16. These periods were the only error-free data sets for zones 1, 2 and 4 (fig. 2.1) and reflect a winter, a mid-season and two summer periods. Due to corruption or failure of many sensors of the BMS, no data during 2014 is available to validate the 9 other zones.

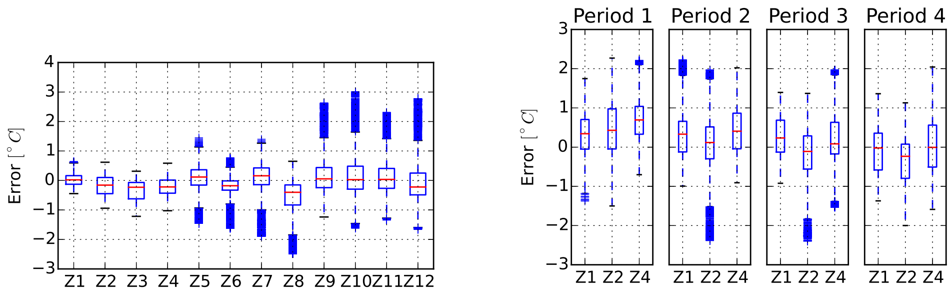
Weather data. The building does not have a local weather station, although during the Christmas experiment the ambient temperature was measured using a dedicated temperature sensor. Therefore, the identification and validation data sets from the BMS are extended with historical data of a weather station in Hasselt obtained from the website `darksky.net`. In order to verify this data, the Christmas ambient temperature from the weather station in Hasselt (F-Hasselt) was compared with those from the airport of Maastricht from both `darksky.net` (F-Maastricht) and `www.wunderground.com` (WG-Maastricht). The comparison shows that the weather data are similar except between the 31st of December and the first of January. The data F-Hasselt is chosen because it is the closest match and because no solar information is available for historical data from `www.wunderground.com`. The direct normal irradiation and the diffuse irradiation on a horizontal surface are computed using the cloud coverage factor from the weather data and the theoretical cloudless solar radiation, which depend on the position of the sun and on the geographical location [10, 6]. Using this conversion, the ambient temperature, direct normal and diffuse horizontal irradiation are known. The Modelica model then makes a geometrical projection on the building surfaces.

Model parameter tuning and validation results. The data obtained during the Christmas experiment (D-Xmax) are used to fine-tune the Modelica model, while the data sets of the year 2014 (D-Y14) are used as validation data. In order to obtain a good temperature fit on D-Xmax, the following tuning is done: the insulation thickness is increased below the apartment and decreased for all roof surfaces that are not below the roof-apartment. The heat capacity of the TABS concrete is doubled from 840 J/kgK to 1680 J/kgK.

For the validation using D-Y14, the tuning made with D-Xmas is kept unchanged and only the internal gains are reduced by 40% compared to their theoretically estimated values. Figure 2.10 shows boxplots of the air temperature error for each validated zone. The horizontal line corresponds to the median, the box to the first and third quartiles, the whiskers to the 95% confidence interval and the crosses to the outliers. Figure 2.10b shows that the errors on the validation data mostly stay below 1 K for the entire data set, which indicates that the Modelica model is a realistic representation of the real building. The other building types are modelled in a similar way. Therefore the validation exercise has not been repeated.

2 Simulation results

This section discusses the simulation results. Figure 2.11 shows the operative temperature of each zone for the whole year and the black lines indicate the comfort range. The heating and the passive cooling mode (active cooling mode is not needed) are indicated with the red and blue background, respectively. Figure 2.12 presents the thermal discomfort computed as number of Kelvin hours outside the comfort range and the maximum and minimum temperature deviation



(a) Christmas experiment. (b) Year 2014.

Figure 2.10: Boxplot of the air temperature error for each zone for the tuning data-set (a) and for zones 1, 2 and 4 using the four validation data sets of one month each (b).

from the comfort range. Figures 2.11 and 2.12 show that the comfort level is good with the exception of zone 11 which shows some undercooling.

Figure 2.13 depicts the heat and cold emission of the AHU and TABS per floor area. The figure shows that the ventilation always cools (around 5 W/m^2). This is due to the fact that the ventilation set-point corresponds to the lower comfort temperature and the ventilation air is therefore not pre-heated up to the zone air temperature. Notice that the ventilation air is rarely actively cooled (see fig. 2.14). Figure 2.14 gives the borefield return water temperature, its heating and cooling loads per month and the heat and cold produced and delivered to the building. Figure 2.14 (b) shows that the building is heating dominated with a netto 80 GJ/year of energy extracted from the borefield. The building is mostly conditioned by its TABS and about 11% of the produced heat is used to pre-heat the ventilation air flow (see fig. 2.14 (c)). The building only uses 15 kWh/m^2/year for heating and 6.5 kWh/m^2/year for cooling (compared to 15 kWh/m^2/year for the total energy used by a passive house).

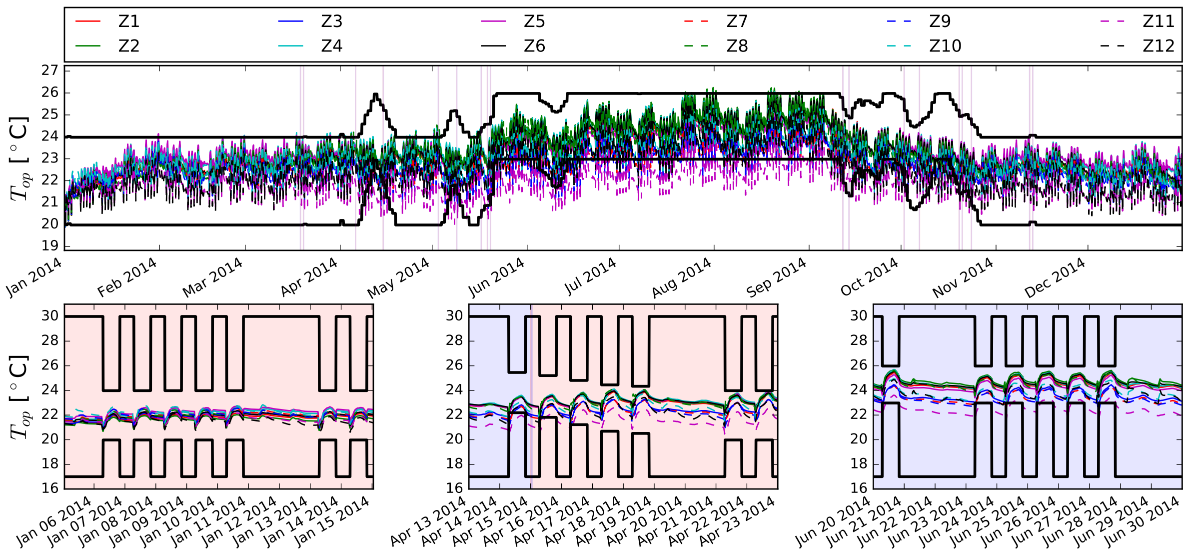


Figure 2.11: Operative temperature of each zone Z_i. The *heating* and *passive cooling mode* are indicated by the red and blue background, respectively.

Appendix A

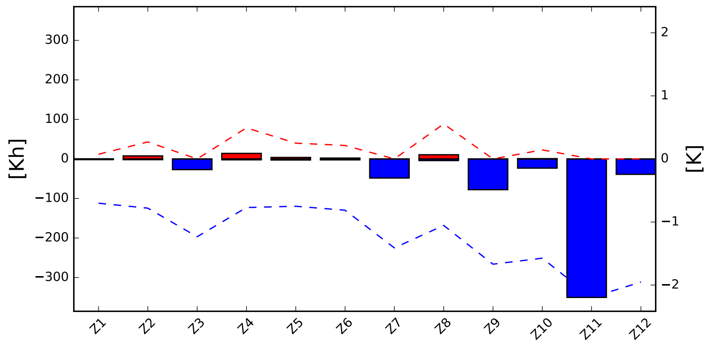


Figure 2.12: Thermal discomfort per zone measured in number of Kelvin hours per year (bars) and yearly maximum temperature deviation from comfort boundaries (dashed lines).

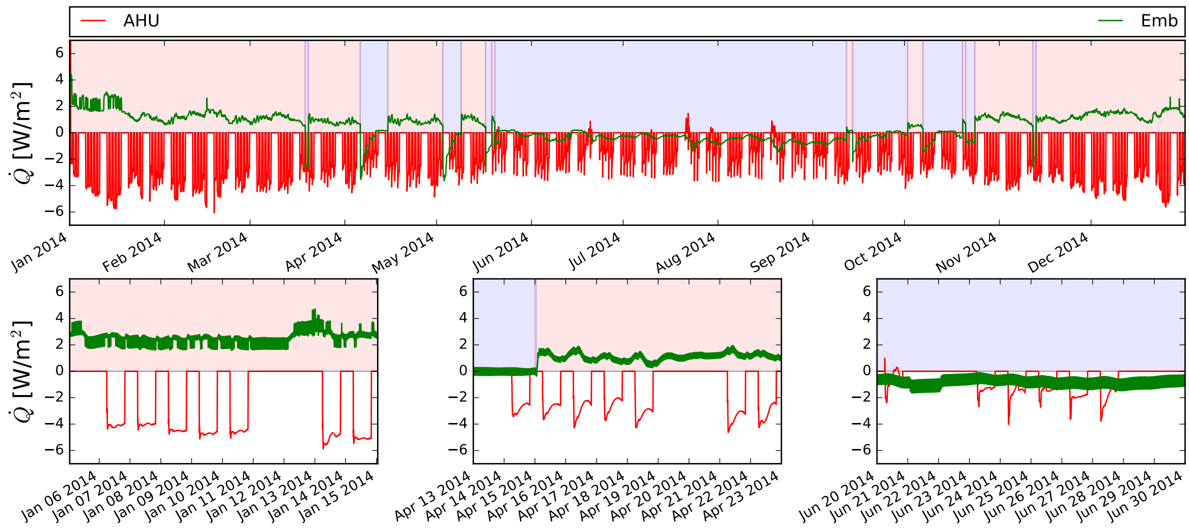


Figure 2.13: Average heating and cooling power per unit floor area delivered by the different emission systems: the ventilation (AHU) and the TABS (Emb).

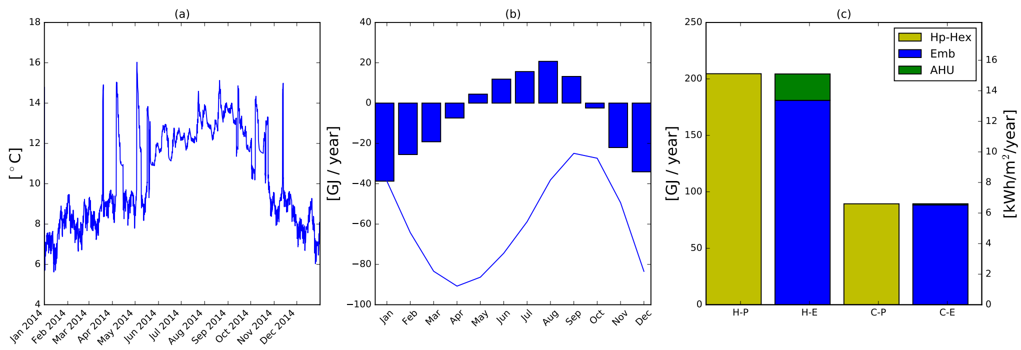


Figure 2.14: (a): borefield return temperature. (b): energy to the borefield (positive = injection). (c): yearly energy used by production systems (P) for heating (H) and cooling (C) and energy delivered by the emission systems (E). The right axis gives the energy in kWh per unit floor area per year.

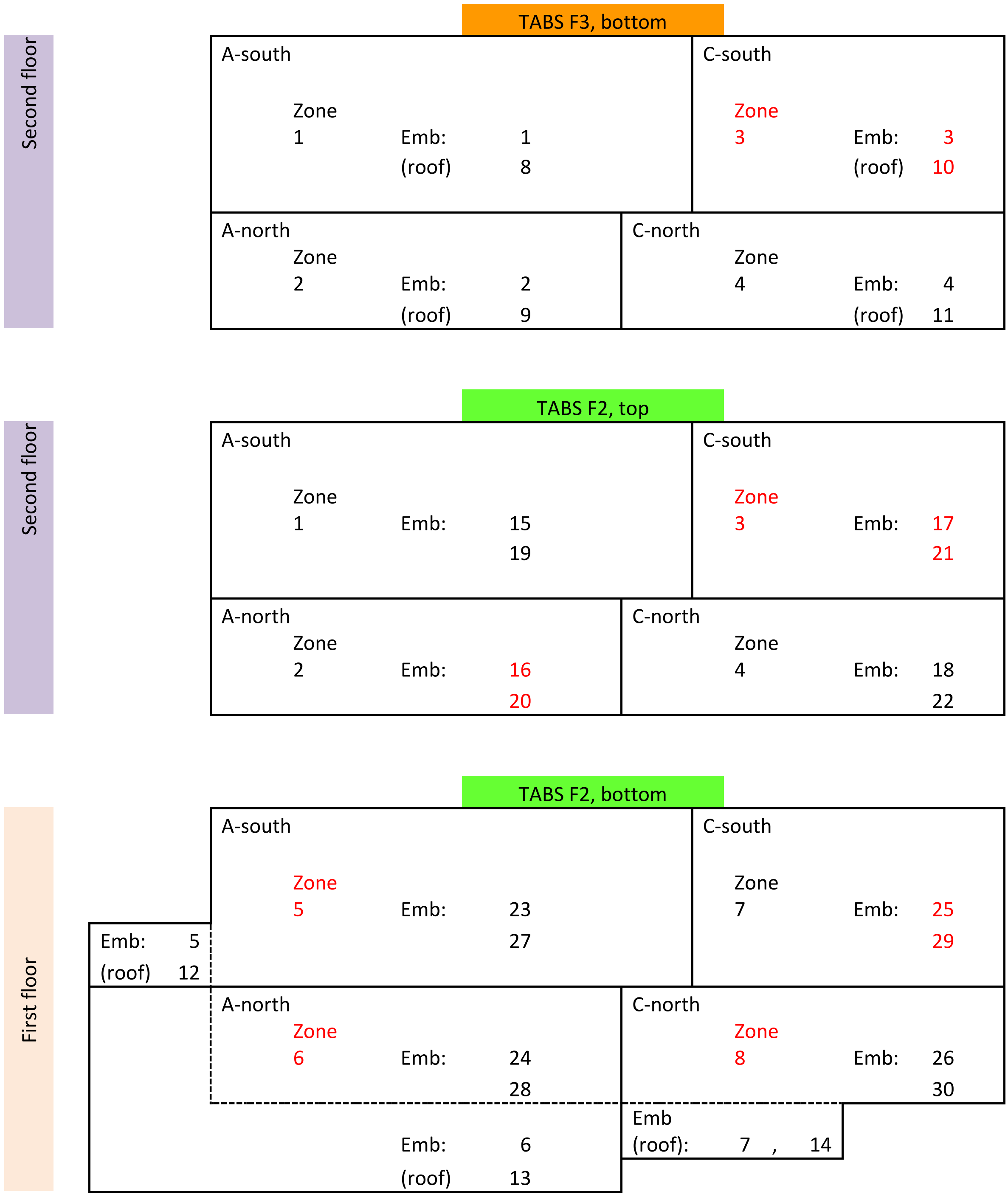


Figure 2.15: Zones and TABS numbering.

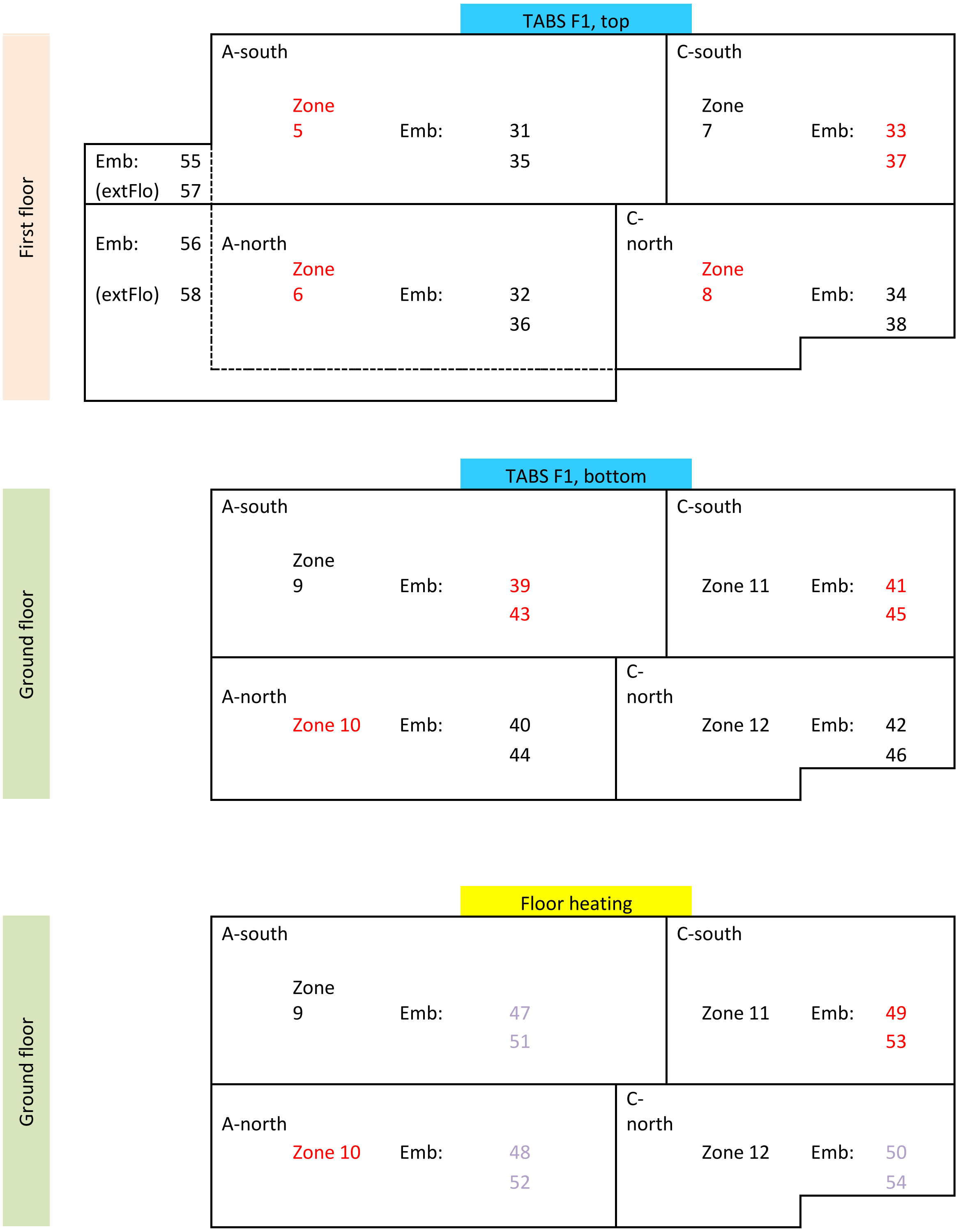


Figure 2.16: Zones and TABS numbering (continued).

Chapter 3

Retirement home: Ter Potterie

- **Type of building**: Retirement home
- **Simulation Software**: Modelica - Dymola
- **Modelica libraries**: IDEAS v.1.0.0, Buildings v.3.0.0, Smartgeotherm v.1.0.0.

The case study building, called *Ter Potterie*, is an retirement home of 121 beds in Brugge (10738 m^2 floor area), Belgium. The building is a so-called *hybrid GEOTABS* building which uses a combination of a ground coupled heat pump to heat and cool through TABS and a gas-fired boiler used to provide the high temperature water used by the radiators and for domestic hot water. The ventilation system is composed of a recovery wheel with by-pass, a heating and a cooling coil and the injection and extraction fans are on-off controlled.

1 Model description

The *Ter Potterie* model is composed of three conditioned floors, an attic and an underground garage. The following sections describe the building envelope (section 1.1), the heating, ventilation and air handling unit (HVAC) (section 1.2), the occupancy and internal gains assumed for the model (section 1.3), and the rule based control (RBC) (section 1.4).

1.1 Building envelope

The general parameters of the building envelope are summarized in table 3.1. In order to limit the model size, rooms with similar function and orientation are lumped together. The resulting model is composed of 18 conditioned zones, the garage and the attic (see fig. 3.1).

Table 3.1: General building parameters.

Floor area	[m^2]	10135	U-value	[W/m^2/K]	0.51
Conditioned volume	[m^3]	41326	Loss area	[m^2]	7913
Window-to-wall ratio	[-]	36%	ACH (n50)	[1/h]	1

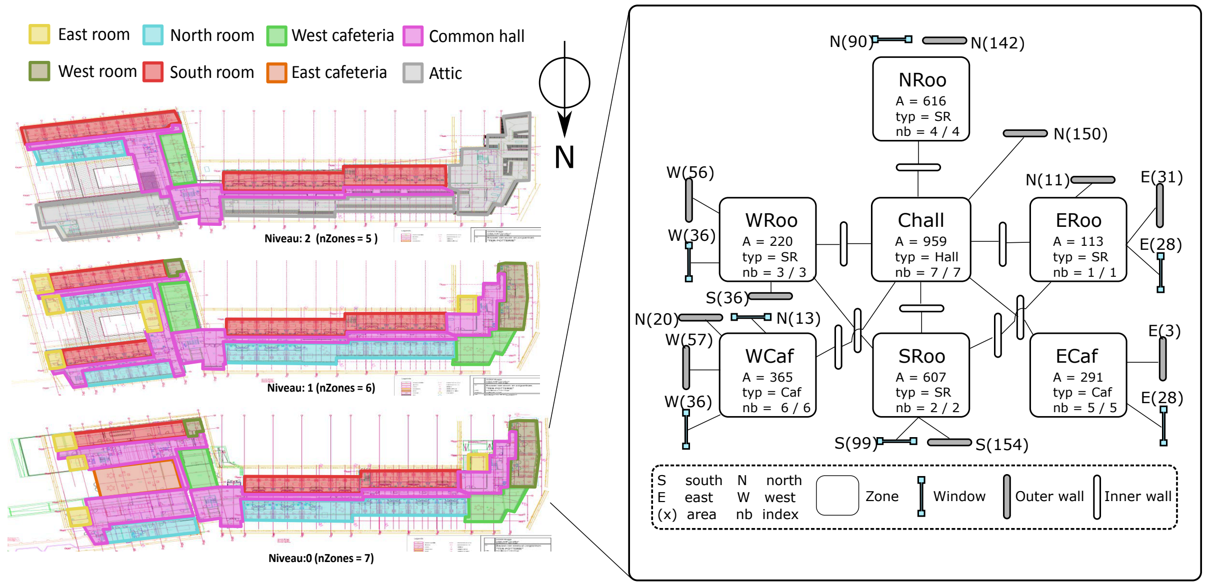


Figure 3.1: Left: Zone layout. Right: zones, walls and windows interconnections for for the ground floor model.

1.2 HVAC system

The building is a *hybrid GEOTABS* building, i.e. the emission system is composed of a combination of TABS, floor heating (FH) and radiators and the production system is composed of a ground coupled heat pump and a gas-fired boiler. The ventilation system is composed of a recovery wheel with by-pass, a heating and a cooling coil and the injection and extraction fans are on-off controlled.

1.2.1 Heat/cold production and emission

Figure 3.2 depicts the hydraulic scheme of the building. The emission system is composed of floor heating at the ground floor, of TABS with the water circuit in the middle of each floor, and of radiators in each room. The nominal mass flow rates and thermal powers of the TABS, floor heating and radiators are listed in table 3.2.

Table 3.2: Nominal mass flow rates, heating powers and cooling powers of TABS, floor heating (FH) and radiators.

Emission	Mass flow rate		Heating power		Cooling power	
TABS	6	[l/h/m^2]	27.9^{*,a}	[W/m^2]	34.8^{*,b}	[W/m^2]
FH	4	[l/h/m^2]	23.2^{*,b}	[W/m^2]	NA	[W/m^2]
Radiator	0.86^{*,c}	[l/h/m^2]	20	[W/m^2]	NA	[W/m^2]
TABS + FH (tot)	54468	[l/h]	267.7	[kW]	242.6	[kW]
Radiators (tot)	8716	[l/h]	170	[kW]	NA	[kW]

* Assuming an inlet-outlet temperature difference of 4 K (a), 5 K (b), and 20 K (c).

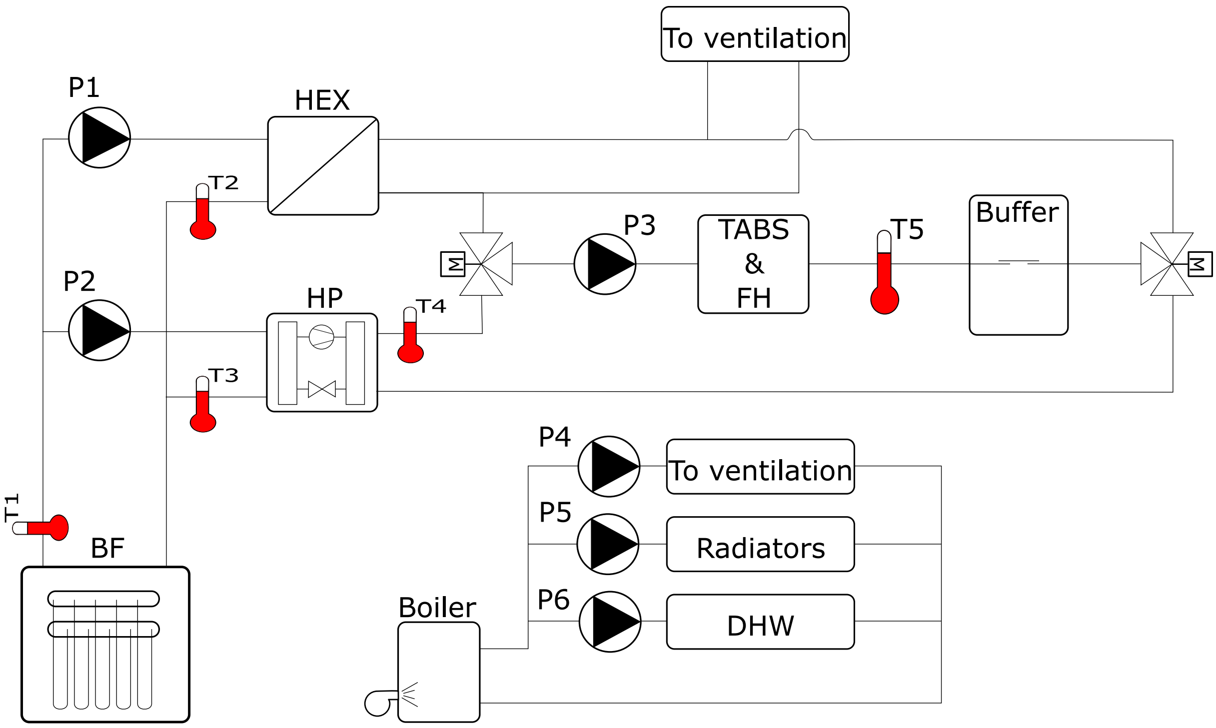


Figure 3.2: Hydraulic scheme. The components are: a borefield (BF), a heat exchanger (HEX), a buffer, a heat pump (HP), a gas-fired boiler, radiators, TABS and floor heating (FH), circulation pumps and domestic hot water (DHW).

The production system is composed of a borefield (BF) consisting of 90 boreholes of 75 m each. All borefield parameters are summarized in table 3.3 and the borehole positions are indicated in fig. 3.3. The borefield is used as a heat source by two heat pumps (Carrier type 61WG 090, 110 kWth) operated in parallel which is approximated in the model by a perfectly modulating single heat pump (HP) of 220 kWth with characteristics given by fig. 3.4. The borefield is used as the cold source by a heat exchanger (HEX) of 260 kW. While in reality the borefield and the heat pump and heat exchanger are supplied by two pumps in parallel with some valves to control the distribution, the model uses a simplified approach where two independent pumps (P1 & P2) are used in parallel for each production component. The cold water coming from the HEX or the warm water coming from the HP is fed to the ventilation and to the TABS and FH and the return water is collected in a buffer tank of 1.5 m^3 in order to stabilize the inlet temperature of the heat pump. The building is further equipped with a condensing gas boiler which supplies the domestic hot water (DHW), the hot water for the radiators and the heating load of the ventilation. The efficiency of the boiler as a function of its set-point temperature is shown by fig. 3.5.

Table 3.3: Borefield parameters

Layout			Borehole			Ground			Grout		
# bh	90	[-]	D_{bh}	160	[mm]	T_0	12.6	[°C]			
Type	2U	[-]	D_{pipe}	32	[mm]	λ	2.48	[W/(m.K)]	λ	0.8	[W/(m.K)]
H	75	[m]	e_{pipe}	2.9	[mm]	ρ	1000	[kg/m^3]	ρ	1000	[kg/m^3]
R_b	0.1	[(m.K)/W]	λ_{pipe}	0.38	[W/(m.K)]	c_p	2430	[J/(kg.K)]	c_p	1650	[J/(kg.K)]

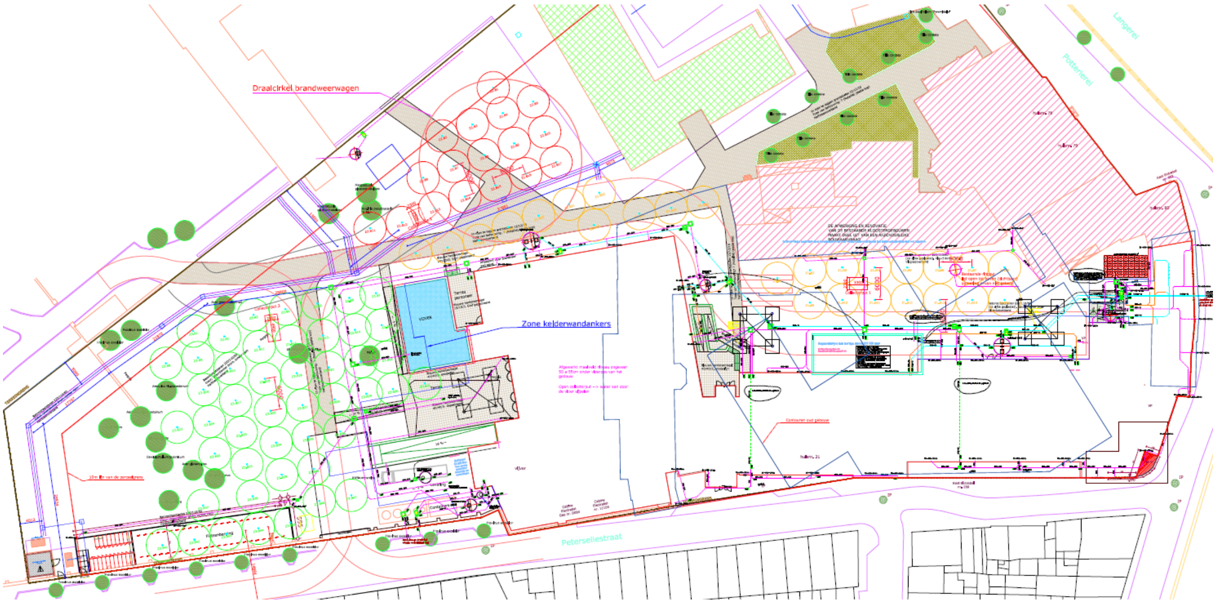


Figure 3.3: Borefield layout. The borefield is divided into three fields around the building (green, red, orange). A minimum distance of 6 m is kept between each borehole.

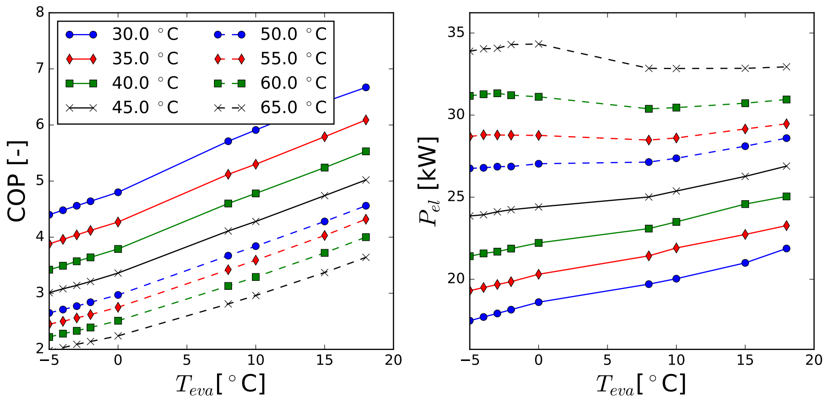


Figure 3.4: Heat pump characteristics (COP and electrical power of the compressor) of *Carrier type 61WG 090* (110 kWth) from its technical description [7].

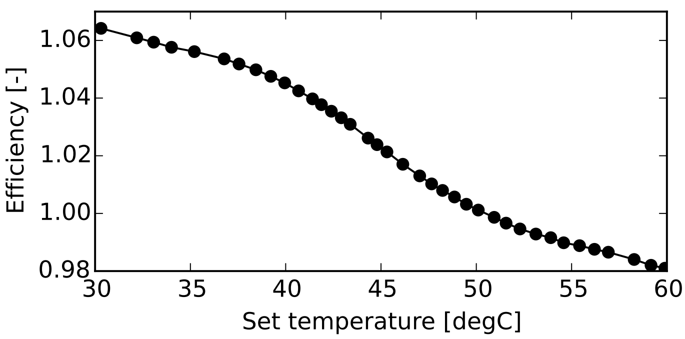


Figure 3.5: Efficiency as a function of the set-point temperature for condensing gas boiler *Riello Tau N 290* (270 kWth) from its technical description [11].

1.2.2 Ventilation system

The ventilation system is composed of a heat recovery with by-pass, a heating and coiling coil, a supply and an extraction fan. The heating coil is connected to the gas-boiler and the cooling coil to the heat exchanger. Figure 2.5 shows a schematic representation of the ventilation model. The ventilation works at nominal condition during the day and at 50% during the night (see nominal conditions in table 3.4 and occupancy in fig. 3.6). For the cafetaria's and common rooms, the ventilation is set to zero during the night. The nominal ventilation flows are taken from the real building and the European standard EN 13779 [1].

Table 3.4: Nominal occupancy and ventilation flow rates for the three room types of the building.

Type of room	Nominal occupancy		Nominal flow rate	
Bedroom	28	[m^2/ pers]	75^{*a}	[m^3/ h / pers]
Hall	28	[m^2/ pers]	45^{*b}	[m^3/ h / pers]
Cafetaria / common	8	[m^2/ pers]	25^{*c}	[m^3/ h / pers]

* based on real building. Equivalent to standard EN 13779 (a: IDA1, b: IDA2, c: IDA3) [1].

1.3 Occupancy and internal gains

The modelled occupancy and internal gains are given by fig. 3.6. The convective, radiative and latent heat production are estimated using the European standard EN 13779 [1] and the detailed description of the appliances and lighting of the bedrooms. The occupancy percentage varies as a function of time and activity of the residents. The domestic hot water (DHW) consumption is based on a similar retirement home (WZC De Vliedberg, [14]) which consumes on average 0.6 m^3/month/bed of DHW at 60°C.

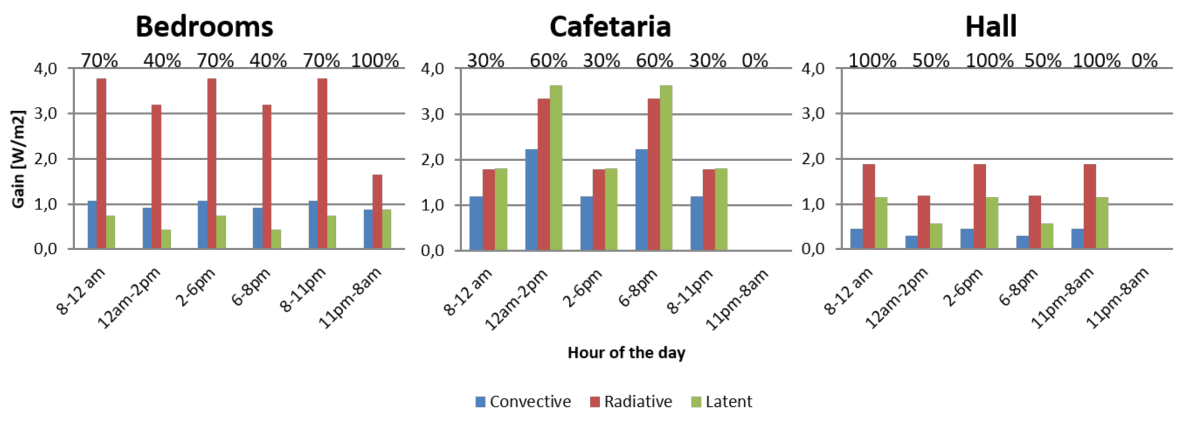


Figure 3.6: Time-dependent internal gains for the three room types of the building. The percentage values given for each time interval correspond to the occupancy compared to the values given by table 3.4 (Nominal occupancy).

1.4 Rule based control

Figure 3.7 sketches the building control: a top level controller (General) decides on the control mode (heating (H), neutral (N) or cooling (C) mode), the lower and upper zone temperature of the comfort range (T_{Low}, T_{Up}), and the water supply temperature $T_{wat,sup}$ to the TABS. The modes are calculated according to the state-machine described by fig. 3.8. The transition between the modes are evaluated only at the start of each hour to avoid fast switching. The comfort ranges are prescribed by the standard EN ISO 7730 [3]. The comfort range varies according to the time of the year (see fig. 3.9).

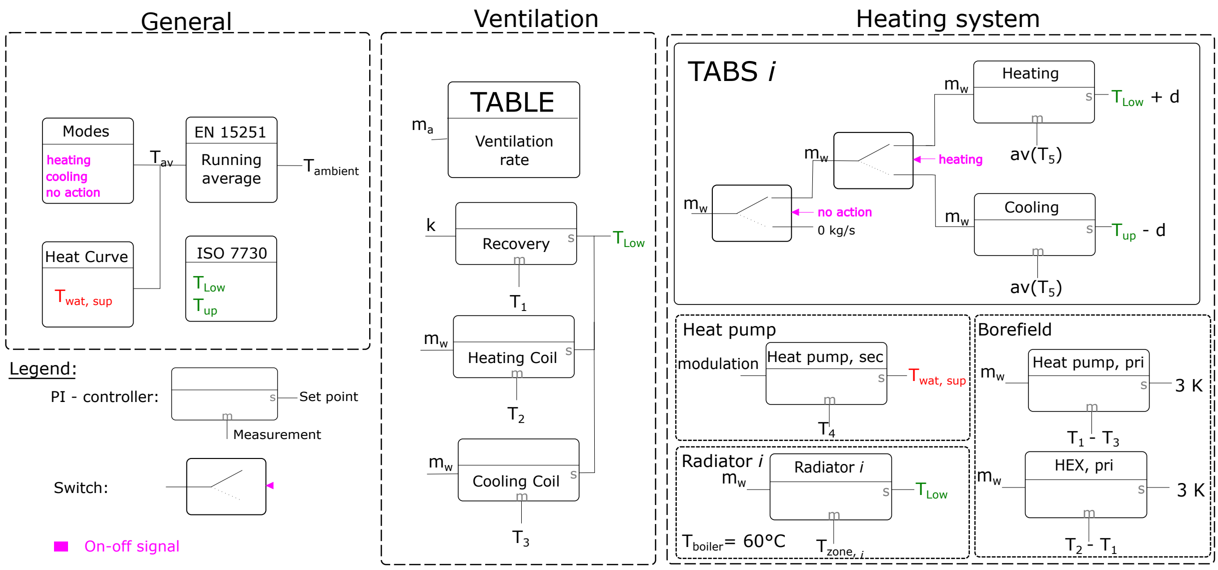
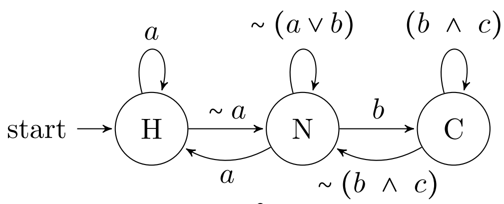


Figure 3.7: Schematic view of the HVAC control. The temperature sensors T_1 to T_3 of the *Ventilation* block refer to fig. 2.5 and T_1 to T_5 from the *Heating / cooling system* block refer to fig. 3.2.



$a = T_{e7d} < 11°C$

$b = T_{e7d} > 15°C$

c = summer

Figure 3.8: Mode selection between heating (H), non-action (N) and cooling (C) modes. T_{e7d} is the weighted 7-days average ambient temperature according to EN 15251 [2], $\vee$ is the logical conjunction (and), $\wedge$ the logical disjunction (or), and ~ the negation (not).

The action of the TABS and FH depends on the mode. During the N mode, no water is circulated. In H or C mode, the water flow is controlled by a PI-controller. The PI tries to set the TABS average return temperature equal to T_{Low} plus an offset d in heating mode and to T_{Up} minus an offset d in cooling mode. The water flow rates to the radiators are also controlled by a PI with the zone temperature as measured input and T_{Low} (without offset) as set-point. The modulation of the heat pump is also controlled by a PI controller such that it delivers water at $T_{\mathrm{wat,sup}}$. Finally, two PI controllers ensure that the temperature difference between the in- and outlet of the primary side of the HEX and the HP equals 3 K.

The ventilation is *on* when occupancy is non-zero. Its supply set-point temperature is equal to T_{Low}. The supply air is firstly conditioned by the recovery unit and the by-pass of the ventilation system. If necessary, the air is further conditioned by the heating and the cooling coil controlled by a PI-controller. The water to the coils is coming from the boiler and the heat exchanger. The ventilation can therefore heat or cool in any mode.

2 Simulation results

This section discusses the simulation results. Figure 3.9 shows the operative temperature of each zone for the whole year and the black lines indicate the comfort range. Figure 3.10 gives the thermal discomfort computed as number of Kelvin hours outside the comfort range and the maximum and minimum temperature deviation from the comfort range. According to figs. 3.9 and 3.10 the thermal comfort level is good with the exception of zones *1Hall* and *2Hall* (the corridors on the first and second floors) which suffer from some overheating. Notice that the cafetaria temperature is allowed to drop below the lower comfort temperature during the night as they are then not occupied.

Figure 3.11 summarizes the heat and cold emission energies of the AHU, TABS and radiators per floor area. The figure shows that the ventilation always cools (around 2.5 W/m^2). Figure 3.11 also indicates that the radiators are on average not much used (< 1W/m^2) but some of the zones use punctually up to 15W/m^2, especially during the cooling season. Figure 3.12 (c) shows that the radiators deliver about 15% of the heating load. Figure 3.12 gives the borefield return water temperature, its heating and cooling loads per month and the heat and cold produced and delivered to the building. Figure 3.12 (b,c) illustrate that the building is heating dominated with a netto 700 GJ/year of energy extracted from the borefield and that the building uses 50 kWh/m^2/year for heating and 14 kWh/m^2/year for cooling (compared to 15 kWh/m^2/year for the total energy used by a passive house).

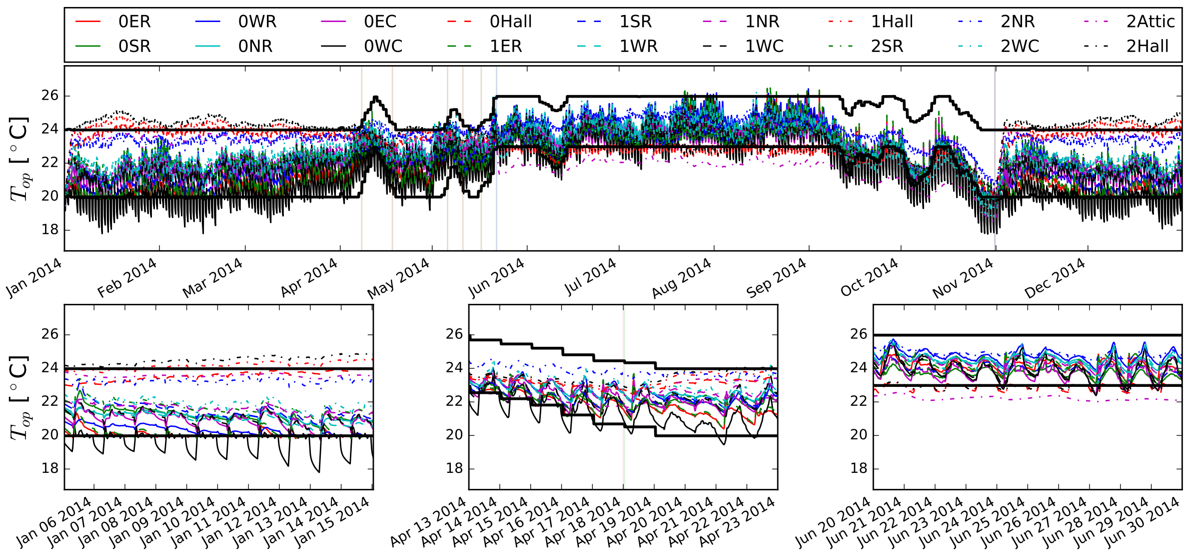


Figure 3.9: Operative temperatures. The *heating, neutral*, and *cooling mode* are indicated by the red, green, and blue background, respectively.

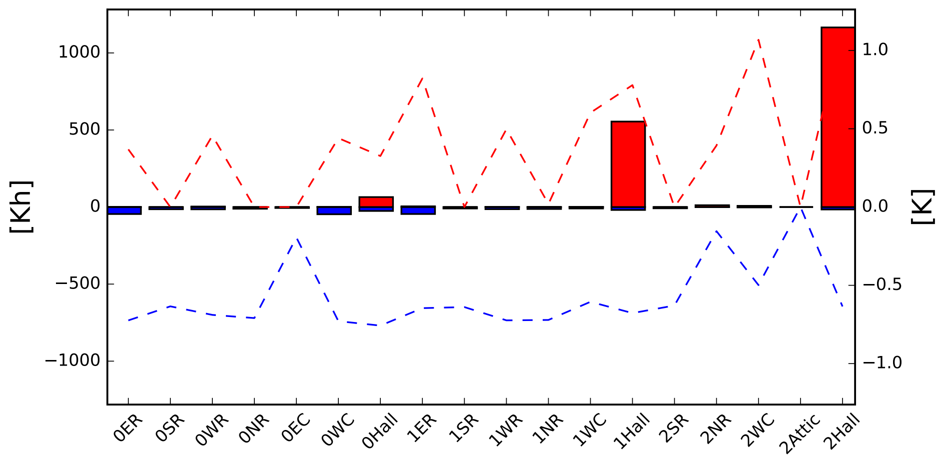


Figure 3.10: Thermal discomfort per zone measured in number of Kelvin hours per year (bars, left y-axis) and yearly maximum temperature deviation from comfort range (dashed lines, right y-axis).

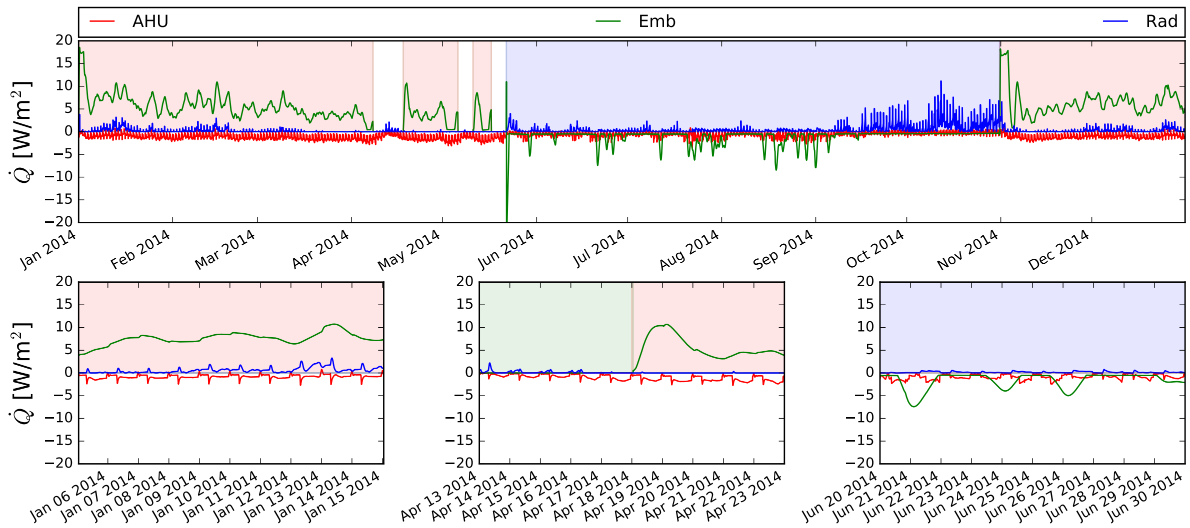


Figure 3.11: Average heating and cooling power per unit floor area delivered by the different emission systems: the ventilation (AHU), the TABS (Emb), and the radiators (Rad).

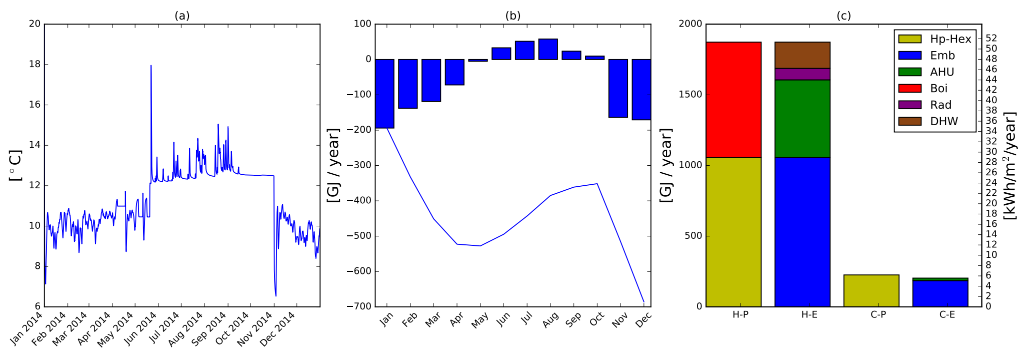


Figure 3.12: (a): borefield return temperature. (b): energy to the borefield (positive = injection). (c): yearly energy used by production systems (P) for heating (H) and cooling (C) and energy delivered by the emission systems (E). The right axis gives the energy in kWh per floor area per year.

Chapter 4

School: KTA Veurne

- **Type of building**: School
- **Simulation Software**: Modelica - Dymola
- **Modelica libraries**: IDEAS v.1.0.0, Buildings v.3.0.0, Smartgeotherm v.1.0.0.

The case study building, called *KTA Veurne*, is a secondary school (1800 m^2 floor area) located in Veurne, Belgium. The building is a *hybrid GEOTABS* building, i.e. the heat and cold are generated by a ground coupled heat pump and a gas-fired boiler and delivered to the building by floor heating and ventilo-convectors. The ventilation system is composed of a recovery wheel with by-pass, a heating and a cooling coil and the injection and extraction fans are on-off controlled.

1 Model description

The building model of *KTA Veurne* is composed of 2 floors and 15 zones. The zones are of five types depending on their function: class room, teachers room, corridor, sanitary room, and technical room. The following sections describe the building envelope (section 1.1), the heating, ventilation and air handling unit (HVAC) (section 1.2), the occupancy and internal gains assumed for the model (section 1.3), and the rule based control (RBC) (section 1.4).

1.1 Building envelope

The general parameters of the building envelope are summarized in table 4.1. In order to limit the model size, identical class rooms are lumped together. The resulting 15 zones layout is given by fig. 4.1.

Table 4.1: General building parameters.

Floor area	1800	[m^2]	U-value	0.49	[W/m^2/K]
Conditioned volume	6250	[m^3]	Loss area	2160	[m^2]
Window-to-wall ratio	19.4%	[-]	ACH (n50)	1 (2.5)*	[1/h]

* The value between brackets is for the old part of the building (zones 6-9).

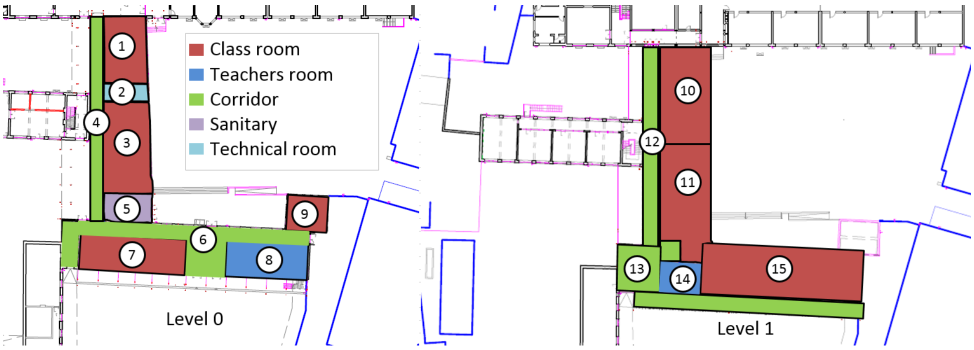


Figure 4.1: Zone layout for the model with the ground floor (left) and the first floor (right). Each number corresponds to the zone number and each color indicates the zone function. Zones 5 to 9 are equipped with ventilo-convectors while the other zones are conditioned using floor heating. While zones 1-5 and 10-15 are newly built, zones 6-9 are kept from the old building.

1.2 HVAC system

The building is a *hybrid GEOTABS* building, i.e. the heat and cold are generated by a ground coupled heat pump and a gas-fired boiler and delivered to the building by floor heating and ventilo-convectors. The ventilation system is composed of a recovery wheel with by-pass, a heating and a cooling coil and the injection and extraction fans are on-off controlled.

1.2.1 Heat/cold production and emission

Figure 4.2 sketches the hydraulic scheme of the building. The emission system is composed of ventilo-convectors for the zones 5 to 9 and of floor heating for the other zones.

Heat is produced by a gas-fired boiler *Remeha Gas 210 ECO* (85 kWth) and by a heat pump of unknown type (50 kWth). The efficiency of an equivalent boiler (*Riello Tau N 290*) and the COP of an equivalent heat pump (VitoCal300GBWS301.A45) are used by scaling the nominal powers. Their characteristics are given by fig. 4.3 and fig. 4.4. Passive cooling is done by a HEX (*ALFA LAVAL CB76-40H*). The heat pump and HEX are connected to a borefield consisting of 16 boreholes (100 m deep) at the primary side and to a buffer tank of 1 m^3 at the secondary side. The gas-boiler is connected to the same buffer tank and it can be used in parallel with the heat pump. All borefield parameters are listed in table 4.2 and the borehole positions are indicated in fig. 4.5.

Table 4.2: Borefield parameters

Layout			Borehole			Ground			Grout		
# bh	16	[-]	D_{bh}	160	[mm]	T_0	12.3	[°C]			
Type	2U	[-]	D_{pipe}	32	[mm]	λ	1.796	[W/(m.K)]	λ	0.3	[W/(m.K)]
Depth	100	[m]	e_{pipe}	2.9	[mm]	ρ	1000	[kg/m^3]	ρ	1000	[kg/m^3]
R_b	0.320	[(m.K)/W)]	λ_{pipe}	0.38	[W/(m.K)]	c_p	2430	[J/(kg.K)]	c_p	1650	[J/(kg.K)]

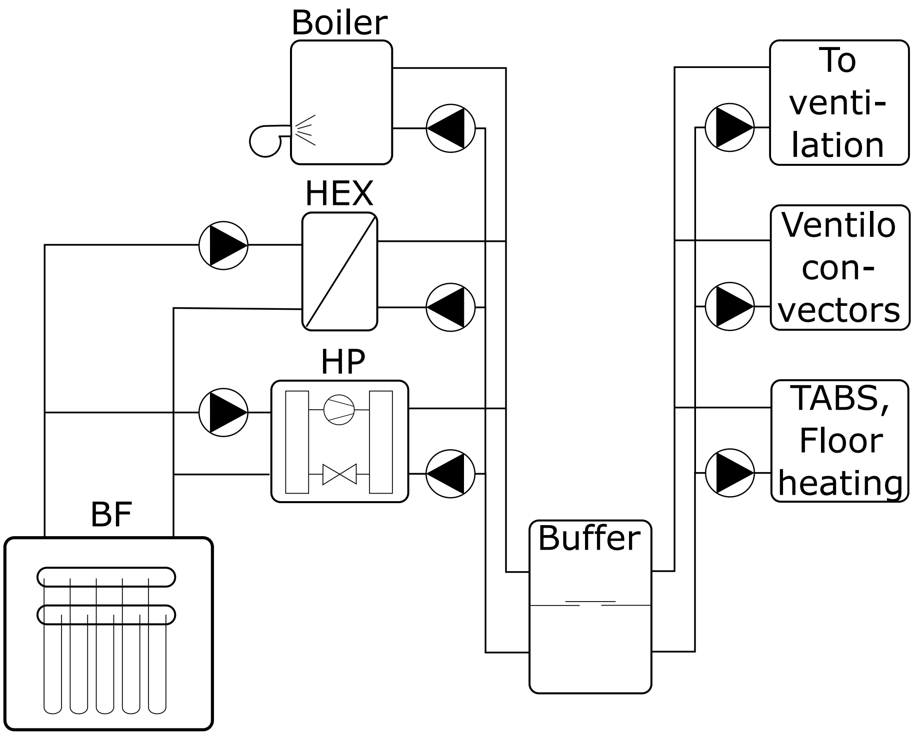


Figure 4.2: Hydraulic scheme. The components are: a borefield (BF), a heat exchanger (HEX), a gas-boiler, a heat pump (HP), circulation pumps, TABS and ventilo-convectors.

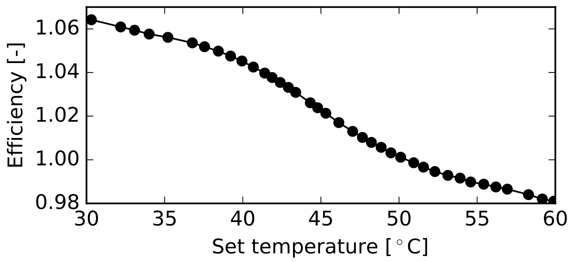


Figure 4.3: Boiler characteristics of the boiler *Riello Tau N 290* from its technical description [11].

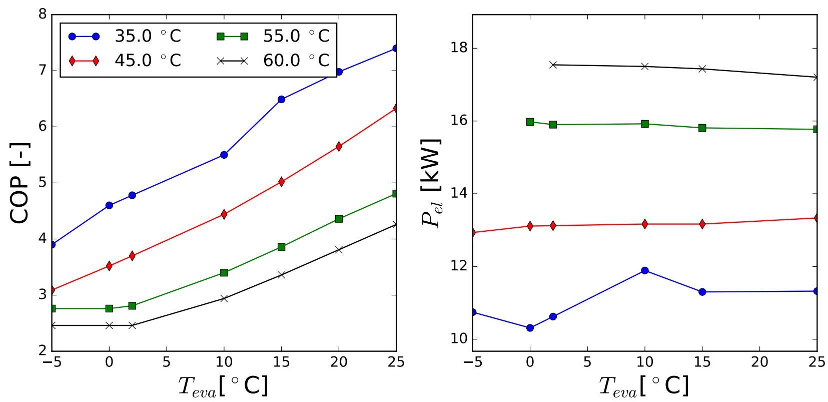


Figure 4.4: Heat pump characteristics of *VitoCal300GBWS301.A45* scaled to 50 kWth from its technical description [12].

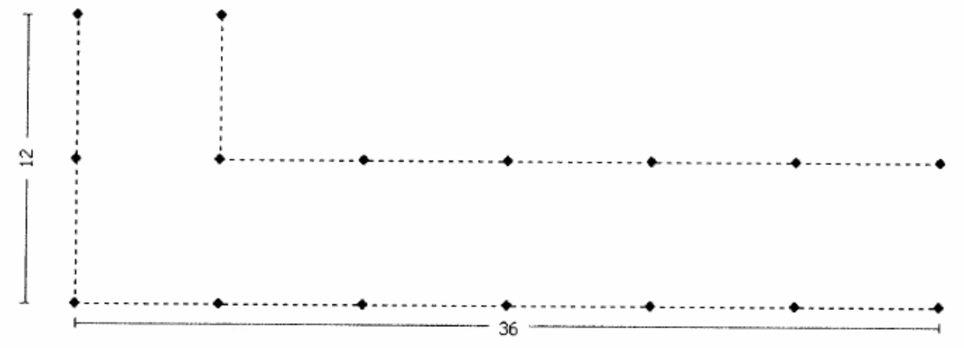


Figure 4.5: Borefield layout. The boreholes are at least 6 m from each others.

1.2.2 Ventilation

The ventilation system is composed of a heat recovery with by-pass, a heating and coiling coil, a supply and an extraction fan. Both the heating and cooling coil are connected to the buffer. The ventilation can therefore only heat or cool when the emission system is in the same mode. A schematic representation of the ventilation model is given by fig. 2.5. The nominal ventilation flow rates and occupant density are taken from Wauman et al. [13]. The ventilation works at nominal condition when occupancy is non-zero and is turned off otherwise (see fig. 4.6). Note that the ventilation is turned on one hour before the students arrive in order to allow pre-heating or pre-cooling by the ventilation system.

1.3 Occupancy and internal gains

The convective and radiative gains and the ventilation flow rates are taken from Wauman et al. [13]. The room-type and time dependent gains are summarized in fig. 4.6.

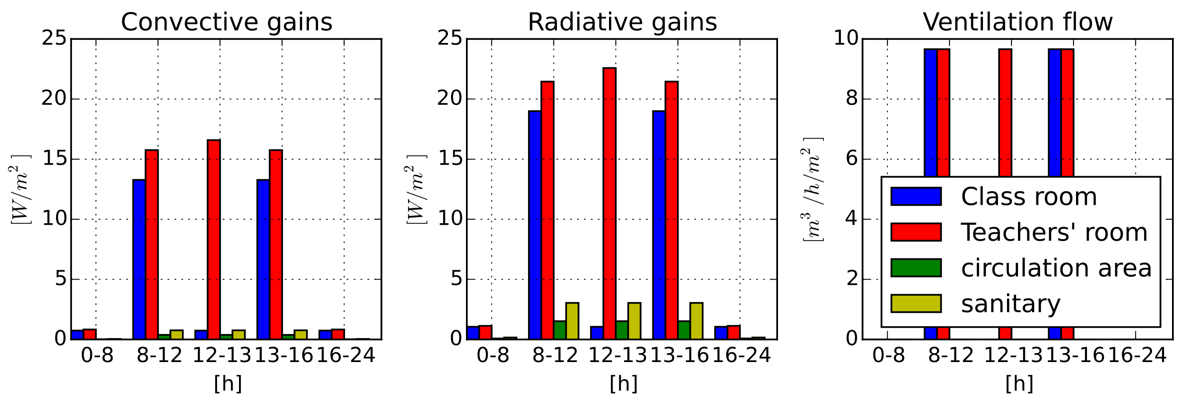


Figure 4.6: Time-dependent convective and radiative heat gains and ventilation flow rate per unit floor area.

1.4 Rule based control

The building control is composed of: i) a top level controller which decides on the control mode (heating (H), neutral (N) or cooling (C) mode), ii) a time varying lower and upper comfort zone temperature bound (T_{Low}, T_{Up}) and iii) a heating/cooling curve which sets the hot and cold water supply temperature $T_{wat,sup}$ for the TABS and the ventilation (eq. (4.1)).

$$T_{\text{wat,sup}} = \begin{cases} -0.22T_{\text{e,av},^{\circ}C} + 28.1 & \text{(heating)} \\ -0.16T_{\text{e,av},^{\circ}C} + 20.3 & \text{(cooling)} \end{cases} \tag{4.1}$$

with $T_{\text{e,av},^{\circ}C}$ the average ambient temperature expressed in °C and computed according to the standard EN15251 [2].

The modes are calculated according to the state-machine described by fig. 3.8. The transition between the modes are evaluated only at the start of each hour to avoid fast switching. The system is further only turned on from Monday to Friday and not on Wednesday afternoon or during July and August. The floor heating id scheduled to only work between 0 AM to 4 PM and the ventilo-convectors from 7 AM to 4 PM. The comfort ranges are prescribed by standard EN ISO 7730 [3]. The lower and upper bounds vary according to the time of the year (e.g. [20,23]°C in winter and [24,26]°C in summer, see fig. 4.7).

In heating mode, the temperature of the buffer is kept at the temperature prescribed by the heating curve by a PI controller which controls the HP modulation and the mass flow rate from the borefield to the HP. When the HP is used at 99% of its maximum power, the boiler is turned on to help loading the buffer tank for a period of minimum 15 minutes. In cooling mode, the buffer tank temperature is maintained by the PI-controlled HEX. Both the primary and secondary sides of the HEX are controlled by the same PI.

The circulation pump of each floor heating and each ventilo-convector is controlled by its own PI-controller with set-point temperature equal to $T_{\text{Low}} + \Delta_h$ in heating mode and $T_{\text{Up}} - \Delta_c$ in cooling mode. The measured temperature is the return water temperature for the floor heating and the zone air temperature for the ventillo-convectors.

2 Simulation results

This section discusses the simulation results. Figure 4.7 indicates the operative temperature of each zone for the whole year and the black lines indicate the comfort range (notice that for the full year plot, only the comfort range for occupancy periods is shown while for the monthly plots, the range for non-occupied period is also plotted). Notice that the school is not conditioned during July and August as the building is not occupied. Figure 4.8 displays the thermal discomfort computed as number of Kelvin hours outside the comfort range and the maximum and minimum temperature deviation from the comfort range. Figures 4.7 and 4.8 show that the comfort level is good with the exception of zone *Z9* which shows some undercooling. The undercooling only happens during the N or the C mode during which this zone still needs heating due to its larger area of external walls and poor insulation. Note that the school is not conditioned during the months July and August.

Figure 4.9 summarizes the heat and cold emission of the AHU, floor heating and ventilo-convector per unit floor area. Note that the ventilation part includes the ventilo-convector powers. Figure 4.10 gives the borefield return water temperature, its heating and cooling loads per month and the heat and cold produced and delivered to the building. Figure 4.10 (b) demonstrates that the building is heating dominated with a netto 65 GJ/year of energy extracted from the borefield. Figure 4.10 (c) shows that the building uses 26 kWh/m^2/year for heating and 10 kWh/m^2/year for cooling (compared to 15 kWh/m^2/year for the total energy use of a passive house). Most of the heat load is covered by the heat pump.

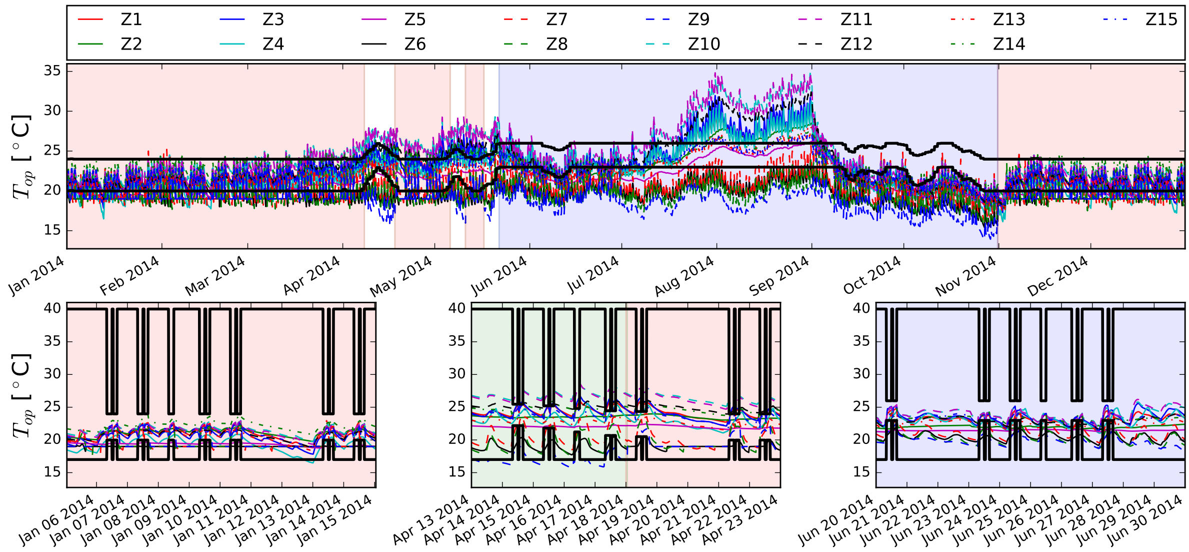


Figure 4.7: Operative temperatures. The *heating*, *neutral*, and *cooling mode* are indicated by the red, green, and blue background, respectively.

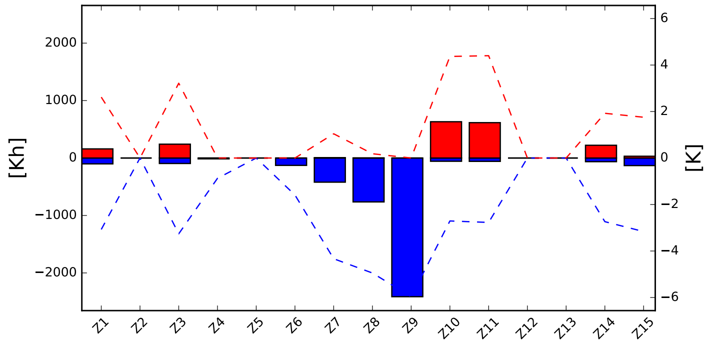


Figure 4.8: Thermal discomfort per zone measured in number of Kelvin hours per year (bars) and yearly maximum temperature deviation from the comfort range (dashed lines).

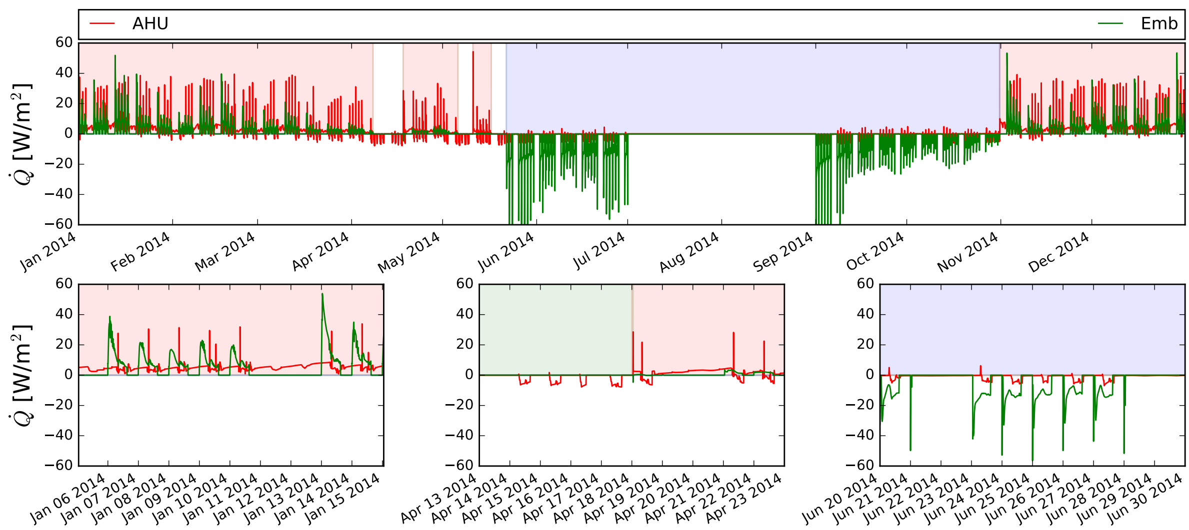


Figure 4.9: Average heating and cooling power per unit floor area delivered by the different emission systems: ventilation (AHU) and TABS (Emb).

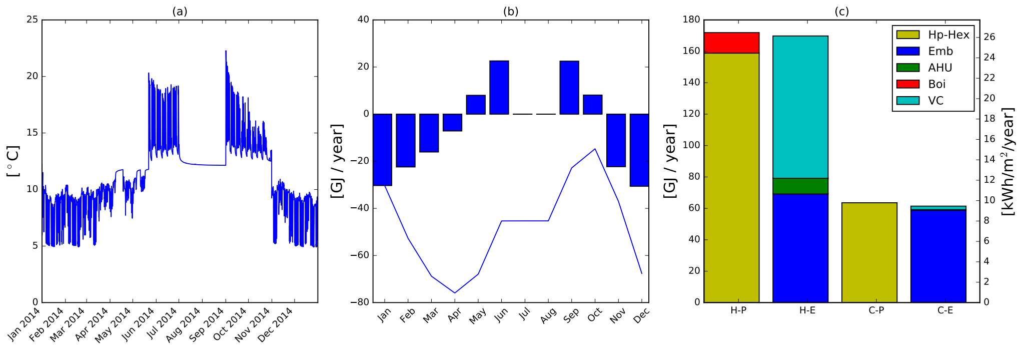


Figure 4.10: (a): borefield return temperature. (b): energy to the borefield (positive = injection). (c): yearly energy used by production systems (P) for heating (H) and cooling (C) and energy delivered by the emission systems (E). The right axis gives the energy in kWh per unit floor area per year.

Chapter 5

Residential building: Evolution

- **Type of building**: Block of flats
- **Simulation Software**: Modelica - Dymola
- **Modelica libraries**: IDEAS v.1.0.0, Buildings v.3.0.0, Smartgeotherm v.1.0.0.

The case study building, called *Evolution*, is a residential building of 10 apartments (820 m^2 total floor area) located in Maldegem, Belgium. The building is a pure *GEOTABS* building, i.e. the heat and cold are generated by a set of ground coupled heat pumps and delivered to the building by TABS. The ventilation is composed of an extraction fan which is controlled according to the CO_2 concentration in the flat, but is not equipped with a heating or cooling coil.

1 Model description

The *Evolution* building model is composed of five floors, each composed of 2 zones (1 zone = 1 apartment). The following sections describe the building envelope (section 1.1), the heating, ventilation and air handling unit (HVAC) (section 1.2), the occupancy and internal gains assumed for the model (section 1.3), and the rule based control (RBC) (section 1.4).

1.1 Building envelope

The general parameters of the building envelope are summarized in table 5.1. In order to limit the model size, each flat is lumped into a single zone. An extra zone is used for the staircase and the lift and a last zone is used for the entrance hall. The resulting 12 zones layout is presented in fig. 5.1.

Table 5.1: General building parameters.

Floor area	[m^2]	818	U-value	[$W/m^2/K$]	0.36
Conditioned volume	[m^3]	2005	Loss area	[m^2]	585
Window-to-wall ratio	[-]	18.4%	ACH (n50)	[1/h]	2

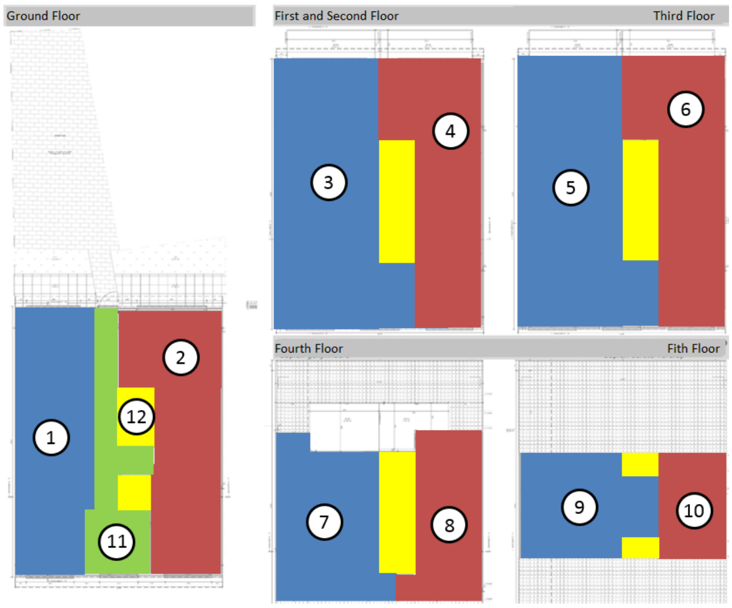


Figure 5.1: Zone layout of the model.

1.2 HVAC system

The *Evolution* building is a pure *GEOTABS* system, i.e. the emission system is composed of TABS and the heat and cold are produced by ground coupled heat pumps. The building is further equipped with a ventilation system composed of an extraction fan which is controlled according to the CO_2 concentration or humidity level in the flat.

1.2.1 Heat/cold production and emission

Figure 5.2 sketches the hydraulic scheme of the building. The emission system is only composed of TABS with a ceiling circuit. Each apartment has its own heat pump which can heat, cool passively and produce DHW. The heat pumps are all the same (*Alpha InnoTec WZS31HKS* (4 kWth)) and their characteristics are given by fig. 5.3. Each heat pump is connected to one common borefield composed of 9 boreholes (125 m deep). All borefield parameters are given by table 5.2 and the borehole positions are listed in fig. 5.4.

1.2.2 Ventilation system

The ventilation system is a *Renson C+ system*, which means that the air extraction is adapted to the measured CO_2 concentration or to the humidity level. The ventilation system is modeled as an ON/OFF extraction system which is turned ON when a minimum of 50 W of convective gain (as a measure for occupancy) is present (the CO_2 concentration is not modeled). The nominal condition corresponds to an air change of 0.4 per hour.

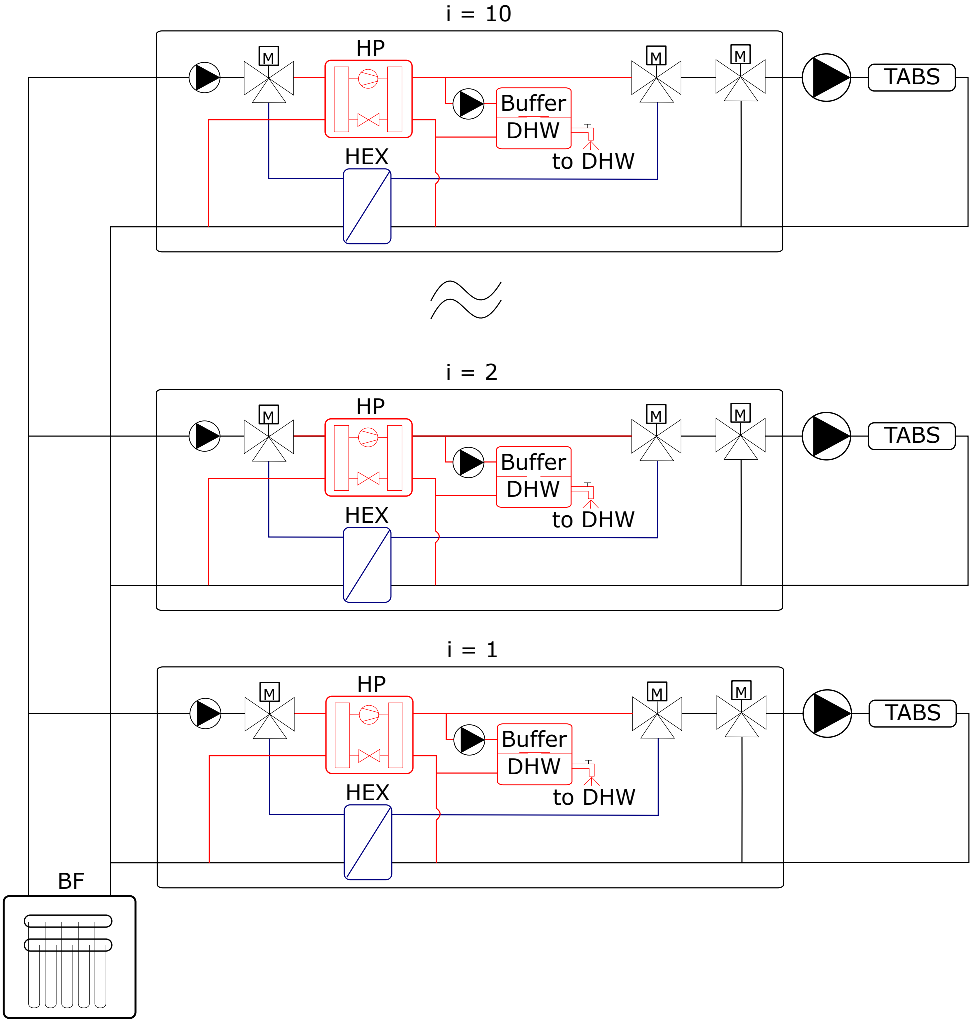


Figure 5.2: Hydraulic scheme. The components are: a borefield (BF), heat exchangers (HEX), a buffer for DHW, a heat pump (HP), three-way-valves, circulation pumps and TABS.

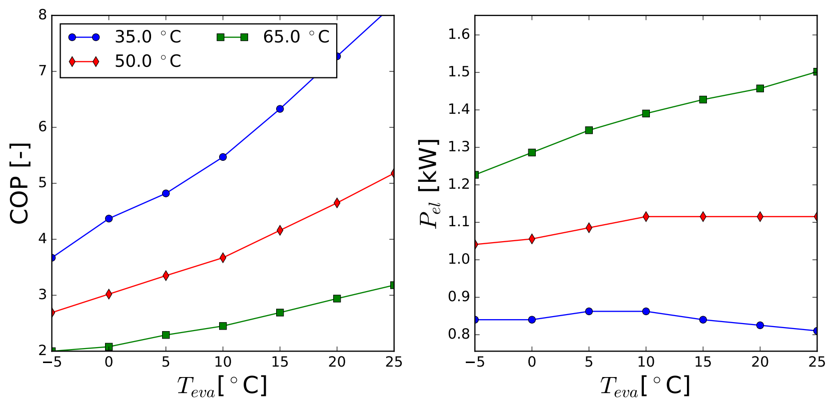


Figure 5.3: Heat pump characteristics of *Alpha InnoTec WZS31HKS* (4 kWth) from its technical description [4].

Table 5.2: Borefield parameters.

Layout			Borehole			Ground			Grout		
# bh	9	[-]	D_{bh}	130	[mm]	T_0	11.3	[°C]			
Type	2U	[-]	D_{pipe}	32	[mm]	λ	2	[W/(m.K)]	λ	0.8	[W/(m.K)]
H	125	[m]	e_{pipe}	2.9	[mm]	ρ	1000	[kg/m^3]	ρ	1000	[kg/m^3]
R_b	0.12	[(m.K)/W]	λ_{pipe}	0.38	[W/(m.K)]	c_p	2500	[J/(kg.K)]	c_p	1650	[J/(kg.K)]

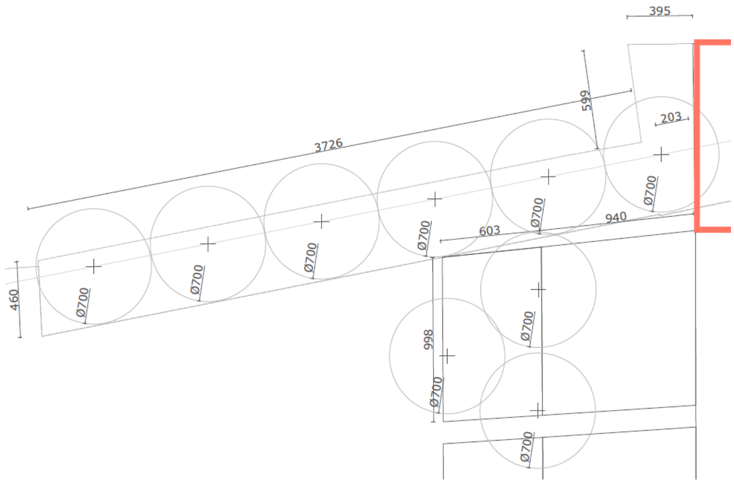


Figure 5.4: Borefield layout. The distance between two boreholes is minimum 7 m.

1.3 Occupancy and internal gains

The convective and radiative gains and the DHW use are taken from the stochastic model StROBe [5]. Each flat and each day has a different profile. Figure 5.5 shows a snippet of one day for the 10 flats. Averaged over a year, each flat uses between 35 and 99 L per day of DHW at 60°C and has on average per day between 82 to 134 W of convective power and between 75 to 118 W of radiative power.

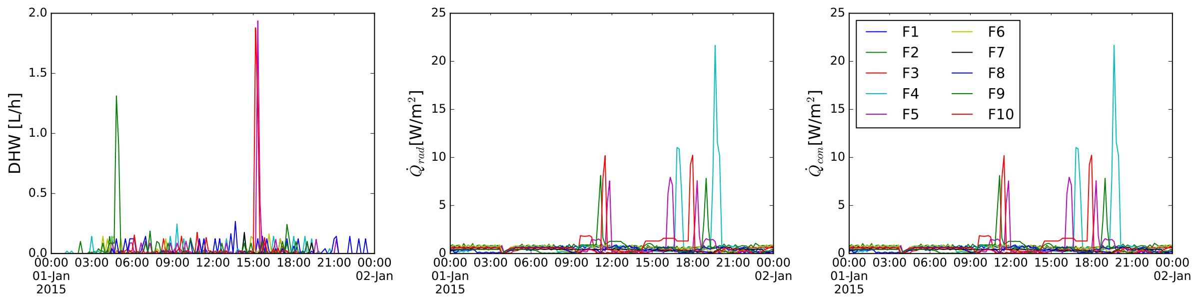


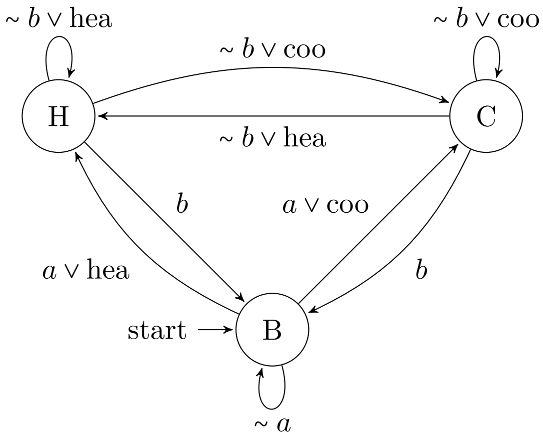
Figure 5.5: Time-dependent domestic hot water (DHW) use, radiative ($\dot{Q}_{rad}$) and convective ($\dot{Q}_{con}$) internal gains illustrated for 1 day for the 10 flats (F_i) based on Baetens and Saelens [5].

1.4 Rule based control

The building control is composed of: i) a top level controller which decides on the control mode (heating (H), neutral (N) or cooling (C) mode), and ii) a flat dependent heating/cooling curve which sets the hot and cold water supply temperature $T_{\text{wat,sup}}$ for the TABS (eq. (5.1), with Δ_i a tuning parameter for each flat and $T_{\text{Low}}, T_{\text{Up}}$ the lower and upper bounds of the comfort range).

The modes are calculated according to the state-machine described by fig. 3.8. The transition between the modes is evaluated only at the start of each hour to avoid fast switching. In H-mode, the supply temperature is delivered by the heat pump (perfect modulation assumed) while in cooling mode a PI controller mixes the return temperature with the water coming from the HEX using the by-pass three-way-valve (see fig. 5.2). In NA-mode, no water is circulated in the TABS and in the other modes the nominal mass flow is kept constant. When the temperature of the DHW tank of the HP drops below 50°C, the supply to the TABS is by-passed and the HP starts loading the DHW tank with water at 55°C. A second state-machine is used to define the HP working state (see fig. 5.6).

$$T_{\text{wat,sup}} = \begin{cases} 0.3(T_{\text{Low}} - T_{e7d}) + T_{\text{Low}} + \Delta_i & \text{(heating)} \\ T_{\text{Up}} - 0.3(T_{e7d} - T_{\text{Low}} + 20) + \Delta_i & \text{(cooling)} \end{cases} \tag{5.1}$$



$$\text{with} \begin{cases} a = T_{\text{Buf}} >= 55°C \\ b = T_{\text{Buf}} < 50°C \end{cases}$$

Figure 5.6: State machine for mode selection between heating (H), loading buffer (B) and cooling (C) mode for the heat pump operation. T_{Buf} corresponds to the DHW buffer tank temperature, *hea* and *coo* indicates the heating and cooling mode as defined in fig. 3.8, ∨ is the logical conjunction (and), and ~ is the negation (not).

2 Simulation results

This section discusses the simulation results. Figure 5.7 illustrates the operative temperature of each zone for the whole year. The comfort range plotted on the lower part of the figure is from flat 1 and it follows the flat occupancy. Figure 5.8 gives the thermal discomfort computed as number of Kelvin hours outside the comfort range and the maximum and minimum temperature deviation from the comfort range. Figures 5.7 and 5.8 show that the comfort level is not high for most of the flats, despite the tuning of the heating/cooling curve of each flat individually. The obtained comfort should be compared with the comfort reached by model predictive control to distinguish the limits of the system from the limits of the controller.

Figure 5.9 summarizes the heat and cold emission of TABS and the AHU per unit floor area. Note that the ventilation is not conditioned. Figure 5.10 gives the borefield return water temperature, its heating and cooling loads per month and the heat and cold produced and delivered to the building. Figure 5.10 (b) demonstrates that the building is heating dominated with a netto 11 GJ/year of energy extracted from the borefield, despite the non-negligible cooling load of the building. The unbalance is due to the DHW production. Figure 5.10 (c) shows that the building uses 14 kWh/m^2/year for space heating and 13 kWh/m^2/year for cooling (compared to 15 kWh/m^2/year for the total energy use of a passive house).

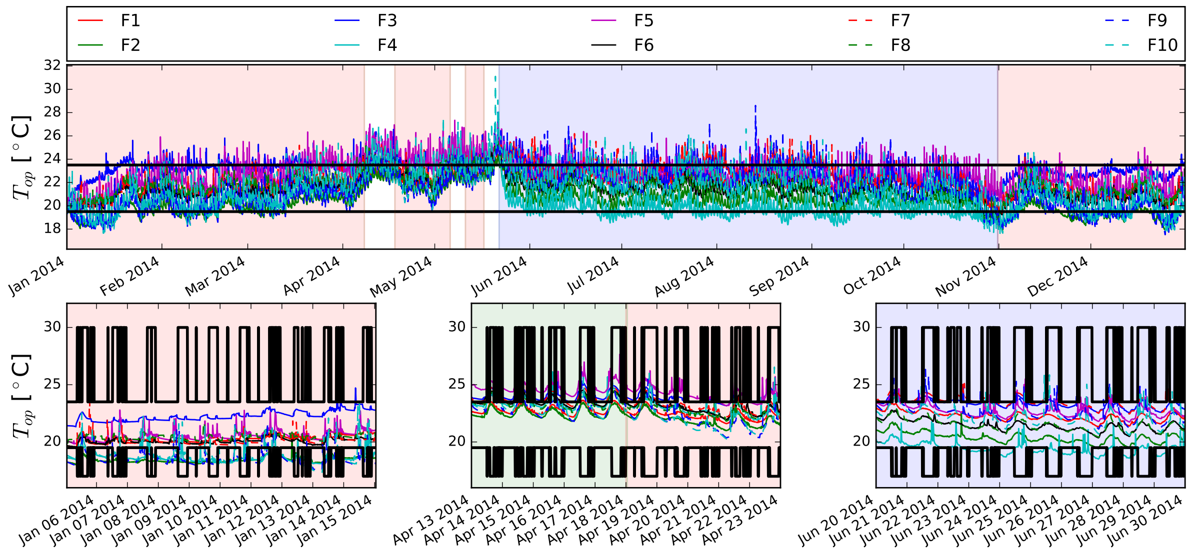


Figure 5.7: Operative temperatures. The *heating*, *neutral* and *cooling mode* are indicated by the red, green and blue background, respectively.

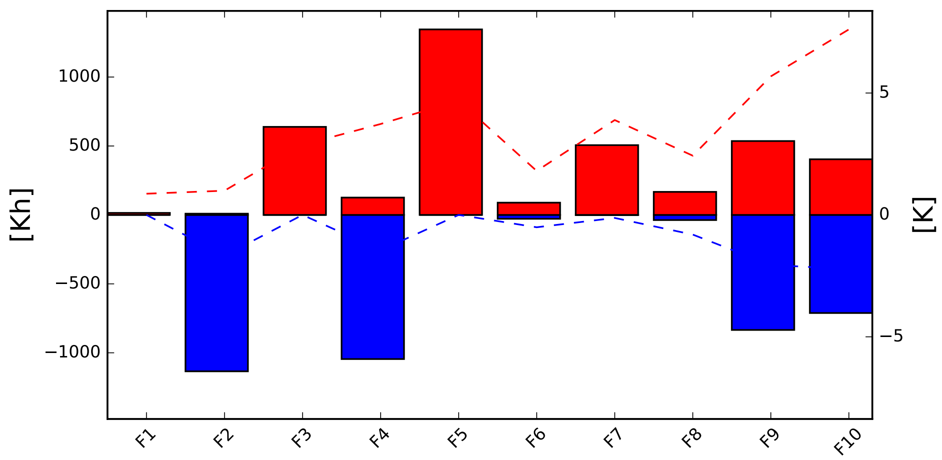


Figure 5.8: Thermal discomfort per zone measured in number of Kelvin hours per year (bars) and yearly maximum temperature deviation from comfort range (dashed lines).

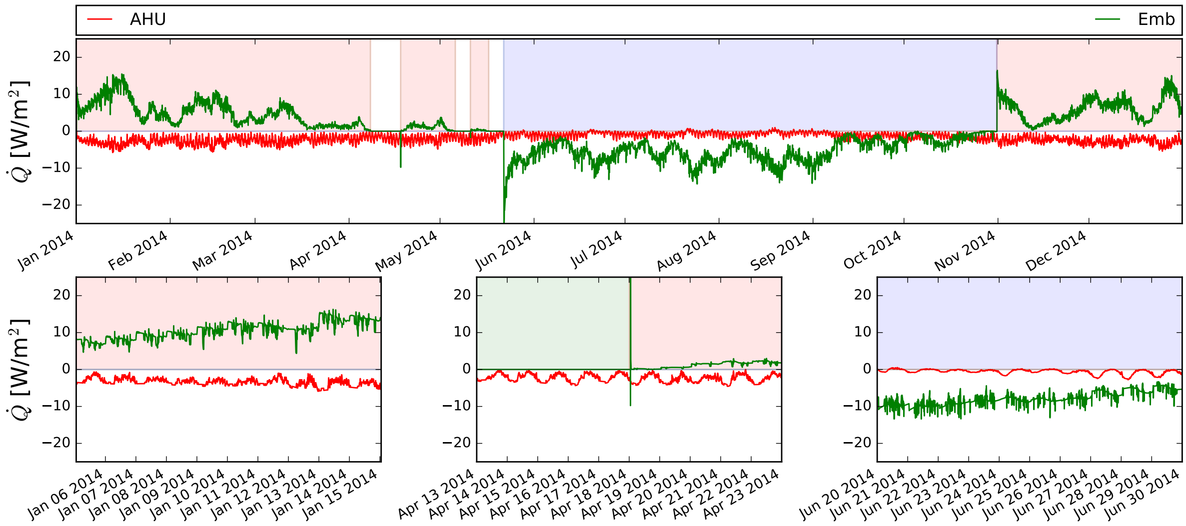


Figure 5.9: Average heating and cooling power per unit floor area delivered by the different emission systems: the ventilation (AHU) and TABS (Emb).

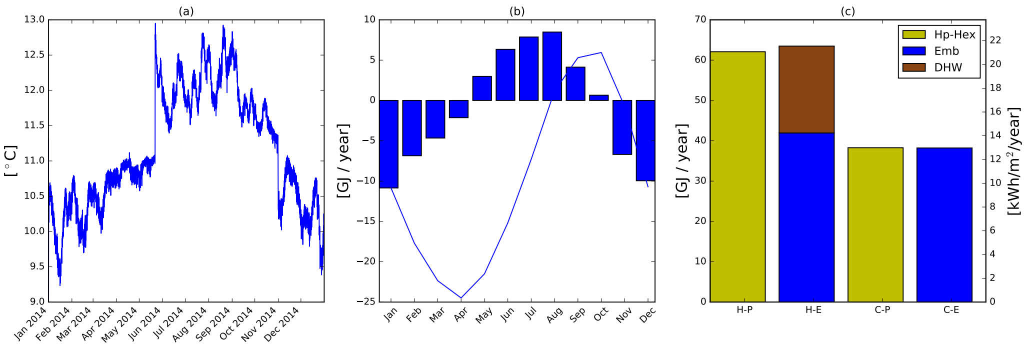


Figure 5.10: (a): borefield return temperature. (b): energy to the borefield (positive = injection). (c): yearly energy used by production systems (P) for heating (H) and cooling (C) and energy delivered by the emission systems (E). The right axis gives the energy in kWh per unit floor area per year.

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